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Additional Experiments on Flowability Improvements of Aviation Fuels at Low Temperatures

Final Report — Volume II

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1.0 SUMMARY

An experimental investigation was performed under NASA Contract NAS3-21977 to study flow improver additives and scale-model fuel heating systems for use with aviation hydrocarbon fuel at low temperatures. The principal objective was to evaluate the effectiveness of these methods in providing flowability and pumpability of fuels at extreme low temperatures when some freezing of the fuel would otherwise occur, by performing tests in a facility that simulated the heat transfer and temperature profiles anticipated in wing fuel tanks during flight of long-range commercial aircraft.

This report describes the results of experiments conducted in a test tank simulating a section of an outer wing integral fuel tank approximately full-scale in height, chilled through heat exchange panels bonded to the upper and lower horizontal surfaces. A separate system heated lubricating oil externally by a controllable electric heater, to transfer heat to fuel pumped from the test tank through an oil-to-fuel heat exchanger, and to recirculate the heated fuel back to the test tank.

Five fuels were used in this study, with freezing points ranging from -50.6 to -28.0°C.

Baseline cold fuel tests to identify partial freezing or "holdup" characteristics were conducted. After the fuel had reached a desired temperature, it was withdrawn from the tank by gravity flow to the boost pump. The accumulation of solid particles remaining at the bottom of the tank after the liquid was withdrawn, was measured by weight difference and defined as holdup.

Heating and recirculating the fuel had a large effect on temperature of the bulk fuel, but had a relatively small effect on temperature of the fuel boundary layer near the chilled surfaces of the tank. In this respect, fuel heating had a measurable influence in reducing holdup. Higher heating rates gave only small decreases in holdup compared with lower rates.

Doping higher freezing point fuels with flow improver additives gave significant reductions in holdup compared to corresponding unheated, untreated baseline tests. Limited tests with conventional freezing point fuels showed very little improvement in holdup for the additives tested.

Correlation of holdup based on a specific boundary layer temperature was generally applicable for tests with heated fuel, as well as with non-heated fuel with or without flow improver additives.

2.0 INTRODUCTION

This report presents the results of a study performed by the Lockheed-California Company under NASA Contract NAS3-21977, "Experimental Evaluation of Scale-Model Fuel Heating Systems," Modification 1.

This experimental study was designed to examine the behavior and effectiveness of flow improver additives and scale-model fuel heating systems in a test facility representative of a section of a commercial aircraft wing fuel tank subjected to a low temperature environment. Pumpability of present and higher-freezing point fuels were evaluated under heated and non-heated conditions with and without additives, at tank temperatures where some freezing of the fuel would otherwise occur.

Limited and costly crude oil supplies and shifts in competing product demands may make it advantageous to refine jet fuels with broader boiling range and compositional tolerances. These changes very likely may raise the freezing point of the jet fuel (Ref. 1 through 6). The ASTM-D 2386 Freezing Point of Aviation Fuels test determines a temperature at which solids disappear, while the ASTM D-97 Pour Point of Petroleum Oils test determines a temperature at which the fuel does not flow when the test apparatus is positioned horizontally (Ref. 7). In practice, the desired measurement is the lowest temperature at which the fuel will flow by gravity, leaving no solid residue. This temperature is between the temperatures determined by the two tests. Fortunately for aircraft operations, the freeze point test assures some conservatism relative to the temperature at which some of the fuel becomes unavailable due to solidification.

The pumpability and low temperature behavior of jet fuels have been studied in tank environments involving tests where fuel was chilled slowly over a period of many hours to maintain a uniform temperature within the tank (Ref. 8, 9, 10). The fuel was then discharged from the tank to determine the fraction of holdup, or frozen, unpumpable fuel. Repeat tests at several temperatures established a relationship of holdup as a function of temperature.

The Lockheed-California Company, under NASA Contract NAS3-20814, conducted tests of the low temperature behavior of aviation turbine fuels under conditions more directly applicable to commercial airplane wing tank environments (Ref. 11 and 12). Fuel in a wing tank model was subjected to chilling by heat transfer designed to reproduce the temperature gradients encountered in flight.

These studies confirmed that fuel can be completely discharged from the tank at temperatures at or slightly below the freezing point. If a small fraction of solid fuel, or holdup, can be tolerated, the useful flow temperature can be further decreased. On the other hand, the wing tank temperature gradients, resulting from the very cold skins and low fuel thermal conductivity, can cause small amounts of holdup under some conditions where the bulk fuel temperature is above the freezing point.

Complete flowability of present jet fuels under extreme cold conditions and use of potential higher-freezing-point fuels would be assured if the wing tank

fuel were heated in flight. Design and analytical work by Boeing (Ref. 13) identified five potential methods for heating fuel in current aircraft types. Two methods, heating with engine oil and heating electrically from additional engine-driven generators, were considered most practical and feasible.

The study reported herein was an investigation of fuels at low temperature in the wing tank simulator apparatus, with a fuel heating system incorporated to represent scale-model concepts of anticipated heating power available from engine oil or from electrical heating. Results reported in the Volume I contractor's report (Ref. 14) show significant benefits from heating and recirculating fuel in reducing holdup.

This report is Volume II of the contractor's report, covering additional experiments after the publication of Volume I (Ref. 14). Low temperature holdup measurements were made with a higher-freezing point ($-33^{\circ}C$) fuel which may be representative of a class of future aviation fuels. Tests were also conducted with this fuel with heating and recirculation for comparison to an unheated, baseline test simulating an extreme cold-day flight. Several rates and variations of heating were investigated. In addition, tests were conducted with this fuel and four other fuels modified with a flow improver additive to assess this technique to reduce holdup as an alternative to heating.

The report includes a description of the test apparatus and procedures, and selected temperature and photographic data. The significance, trends, and possible applications of the results are discussed.

The assistance of Mr. David H. Rehrer, Exxon Chemical Company, in the furnishing and laboratory characterization of the flow-improving additives is gratefully acknowledged. The use of these proprietary materials does not imply either a critical evaluation or an endorsement of these products.

3.0 APPARATUS

3.1 TEST CELL

Experiments with the test tank were performed at the Rye Canyon Research Center of the Lockheed-California Company's Engineering Laboratories. The test cell, located at the east end of Building 209, measures approximately 3.4 meters (11 feet) by 4.6 meters (15 feet). A large window permits observers to view the test cell from the main building.

3.2 TANK CONSTRUCTION

Configuration of the test tank, which was also used in the previous studies (Ref. 11), was designed to simulate a portion of an outer wing fuel tank of a modern commercial jet aircraft. Interior dimensions of the tank are 50.8 centimeters (20 inches) high, 50.8 centimeters (20 inches) wide, and 76.2 centimeters (30 inches) long.

The tank was fabricated from 6061-T6 aluminum alloy sheet, 3.2 mm (0.12 inch) thick for the upper and lower surfaces, and 4.8 mm (0.19 inch) thick for the vertical walls. The lower surface was stiffened by modified I-section aluminum alloy stringers 57 mm (2.40 inches) high. The upper surface Z-section stringers were 71 mm (2.80) inches high. An open "surge box", 127 mm (5.0 inches) high, in a corner between a vertical wall and a stringer, surrounded the bottom fuel exit. A small, free-swinging "flapper" check valve installed in one side of the surge box permitted fuel to enter the surge box from the bay between the stringer and the vertical wall. Figure 1 is a plan view sketch of the test tank, showing the bottom stringers, observation windows, and fuel plumbing. The longer dimension, parallel to the stringers, is spanwise with respect to the airplane wing construction. The tank was mounted with this dimension at a 4° angle to the horizontal, with the surge box at the low end, to simulate airplane wing dihedral. Figure 2 is a cross-section of the test tank.

Assembly of the tank was accomplished primarily by riveting, but one end of the tank was removable. The tank was sealed with fuel tank sealant, and the interior was painted with a urethane anti-corrosion coating as used on the L-1011 airplane.

Figure 3 is a photograph of the interior of the tank. The tank had viewing windows on all four sides. Viewing windows had a double pane construction, with the space between the panes evacuated to prevent moisture condensation and improve insulation.

3.3 FUEL SYSTEM

Fuel exited from the tank through a 48.3 millimeter (1.90 inch) diameter opening in the bottom of the tank at the corner of the surge box (Figure 1). Over this opening was an aluminum disc perforated with 6.4 millimeter (0.25 inch) diameter holes. An aluminum tube, tapering from 50.8 millimeters (2.00 inches) outside diameter at the tank to 31.8 millimeters (1.25 inches) diameter, connected the test tank to a small chamber housing an aircraft-type 24 volt direct current boost pump (Figure 4). This was a centrifugal pump used

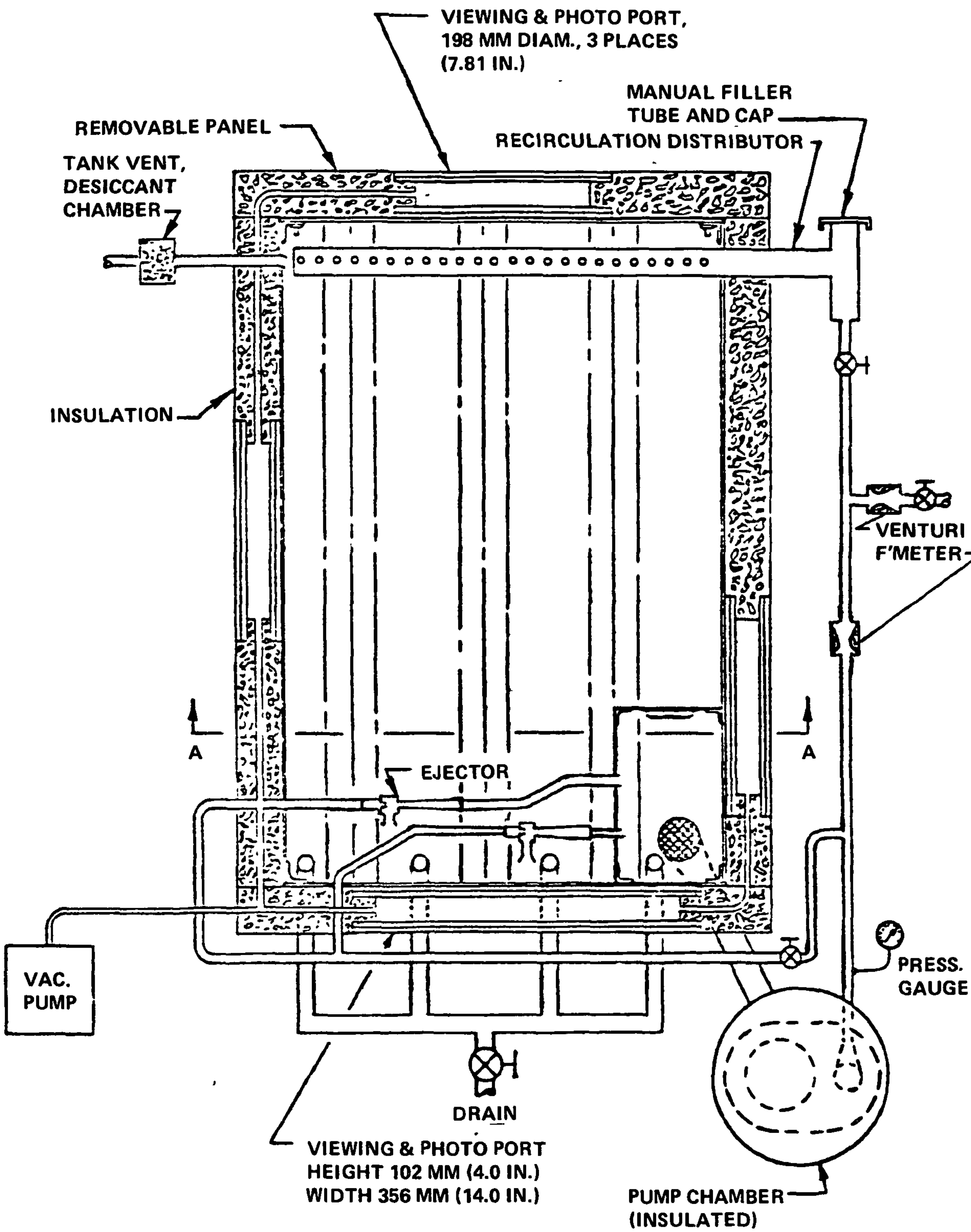

FIGURE 1 - PLAN VIEW OF TEST TANK

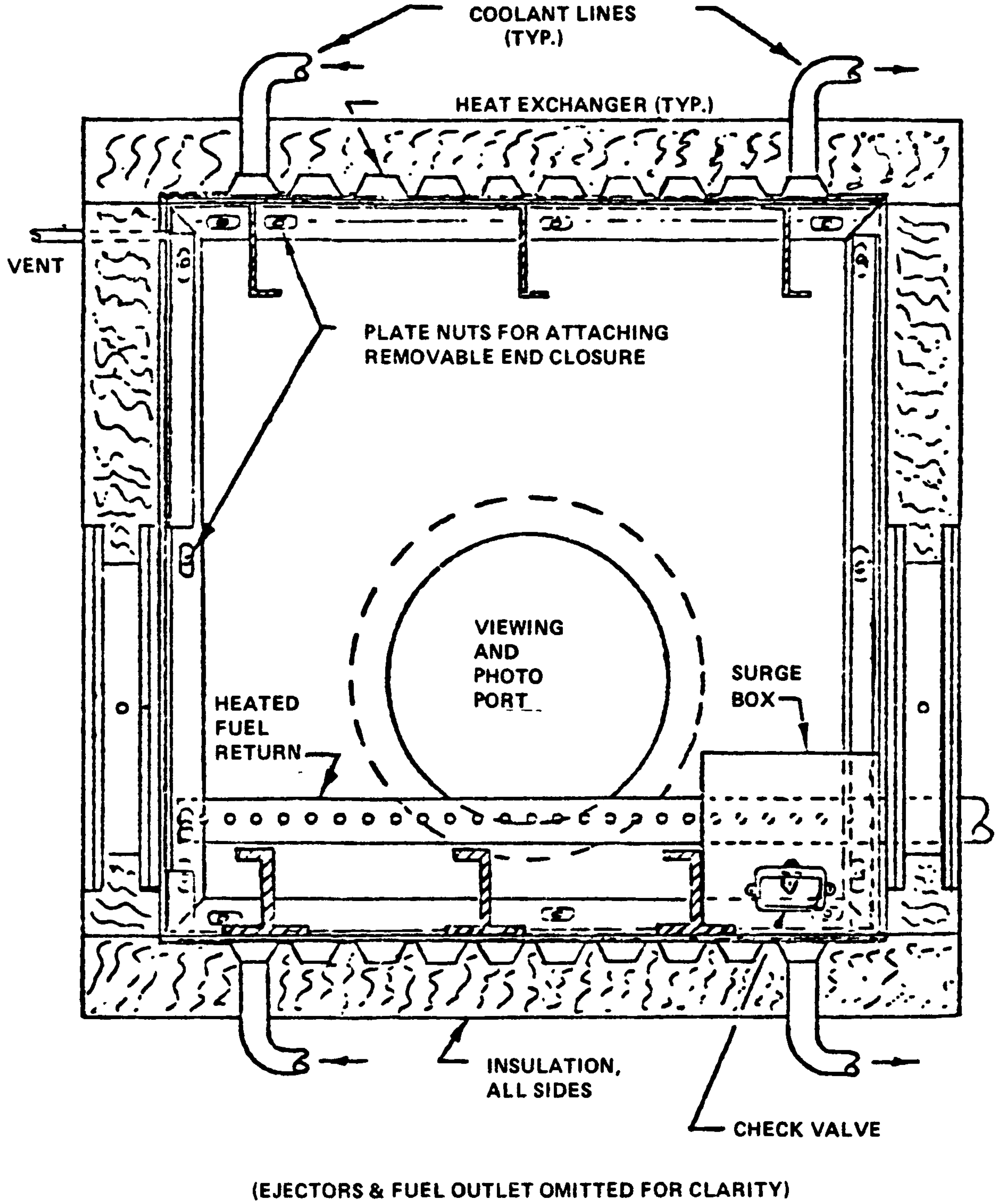

FIGURE 2 - CROSS-SECTION OF FUEL TEST TANK
(VIEW AA IN FIGURE 1)

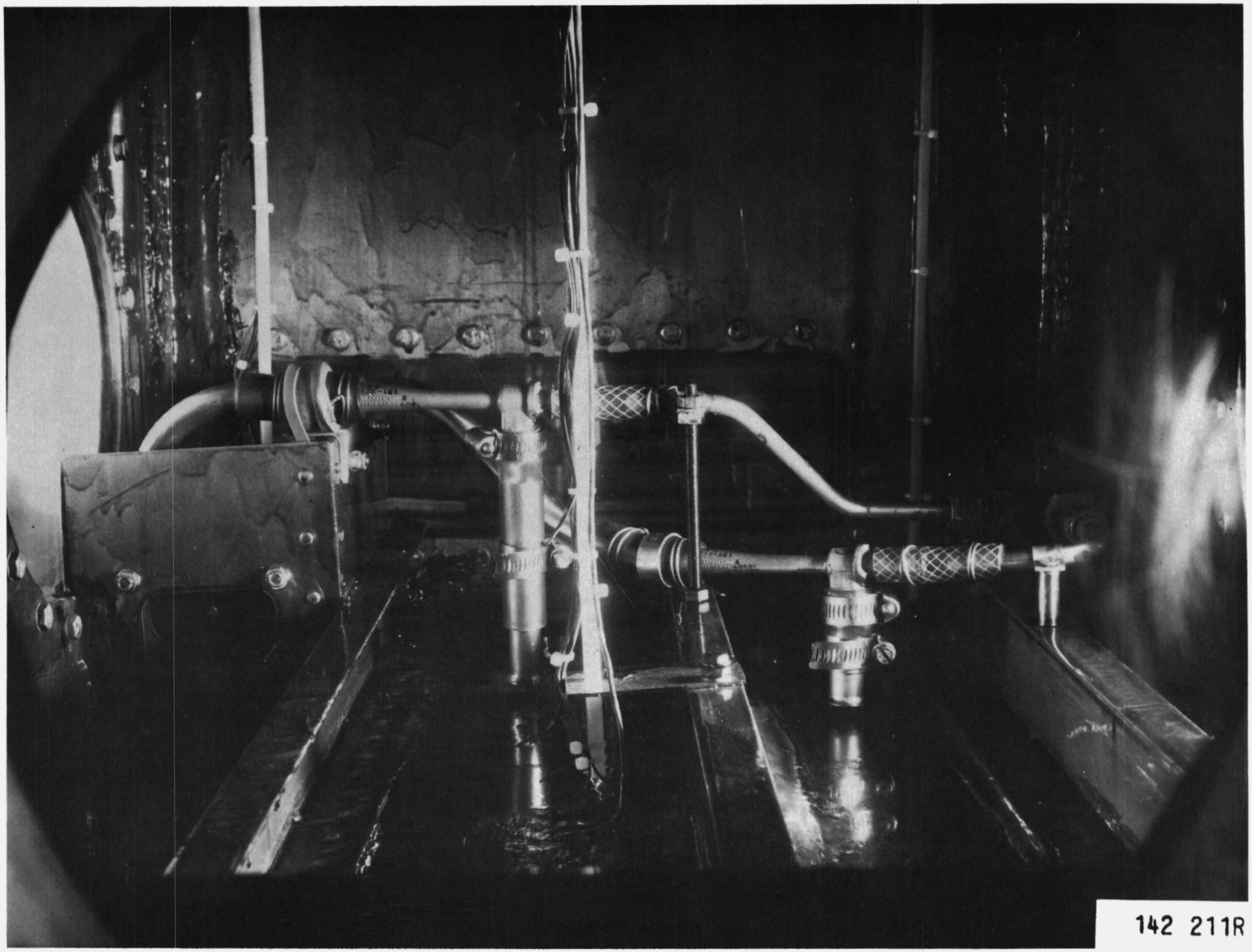

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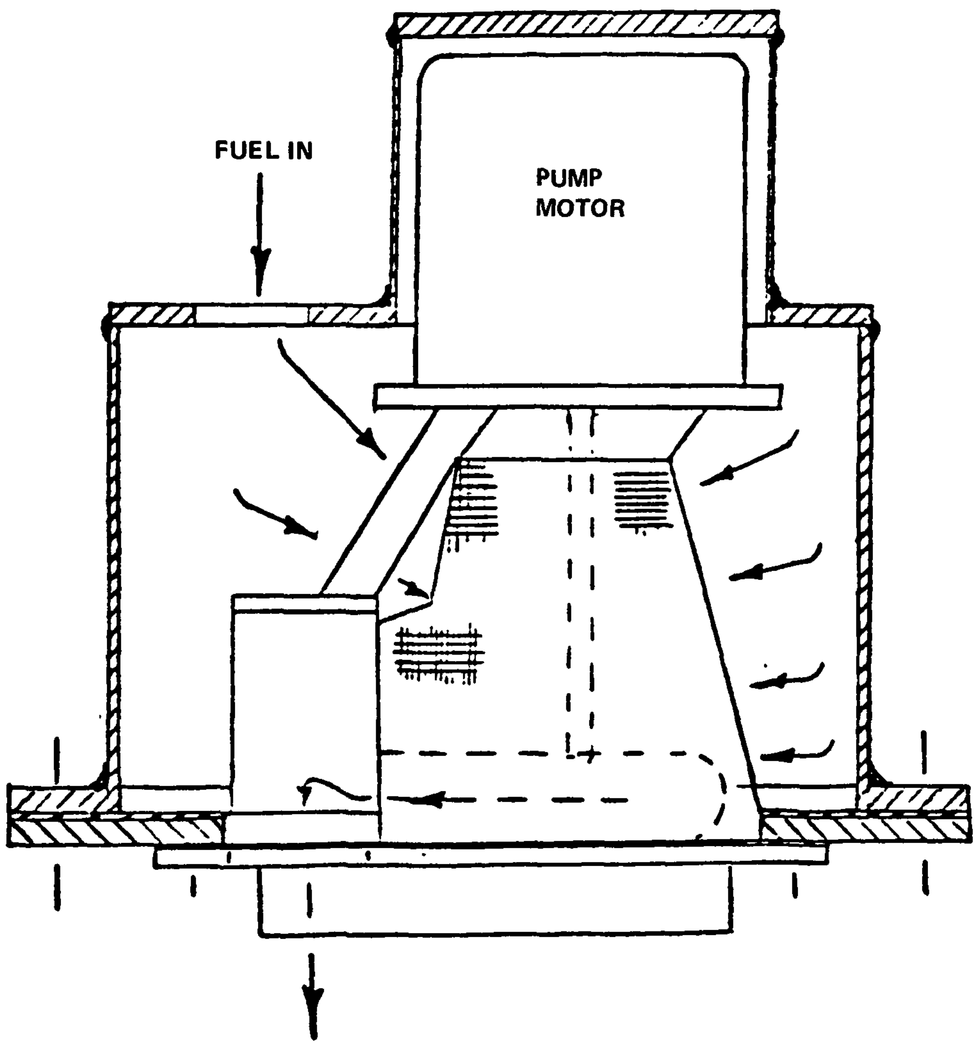
FIGURE 3 - TANK INTERIOR VIEWED THROUGH WINDOW OPPOSITE PUMP INLET



(FITTINGS OMITTED FOR CLARITY)

FIGURE 4 - CROSS-SECTION OF BOOST PUMP INSTALLATION

on early jet fighters and was selected for its relatively small power requirements of approximately 360 watts, thereby minimizing heat rejection to the fuels. By comparison, one L-1011 fuel boost pump is almost 10 times that power. The pump assembly incorporated a large area 8-mesh screen surrounding the impeller inlet. The dome around the pump motor inhibited fuel circulation and minimized heat rejection to the fuel. The pump discharged into a line of 12.7 millimeters (0.50 inch) outside diameter. This line branched in one direction to supply motive flow through a control valve to two small ejectors, or jet pumps, which could remove fuel from two of the bays formed by the bottom stringers. These ejectors discharged into the surge box. A branch and shutoff valve in the other direction would permit fuel to be pumped either into or out of the tank. A tee and valve in this branch controlled fuel flow to the heat exchanger. Adjacent to the tank the line size was increased to 31.8 millimeters (1.25 inches) outside diameter. A tee in this line allowed fuel to recirculate into the tank through a perforated tube extending across the tank, and was also connected to a standpipe which served as a dipstick well, or as a manual filler; it was capped during testing. Filling of the test tank usually was accomplished by pumping fuel through the perforated recirculation return tube in the tank.

The tank was vented through a 12.7 millimeter (0.50 inch) tube penetrating the test tank vertical wall as high as possible near the removable end panel. A desiccant chamber prevented the entry of atmospheric moisture during chilldown.

Nearly all liquid fuel could be discharged by means of the boost pump and ejectors. Additional drainage of small quantities of trapped fuel, or total flushing, could be accomplished by small drains installed in each bay between the bottom of the stringers.

3.4 COOLING SYSTEM

Since the test tank simulated a portion of an aircraft fuel tank, the upper and lower surfaces represented wing skins and were provided with cooling panels to simulate in-flight heat transfer to the atmosphere. Each panel consisted of a flat stainless steel plate 50.8 centimeters (20 inches) by 76.2 centimeters (30 inches) to which was spot-welded another stainless steel plate which had been embossed to provide a serpentine passage for the coolant flow. The panels were bonded to the tank shell with a thermally-conductive filler.

The coolant system consisted of a reservoir of methanol which was chilled by liquid carbon dioxide. In turn, the methanol was circulated to the heat exchange panels by a centrifugal pump (Figure 5). The flow of refrigerated methanol was divided just outside the test tank to supply the upper and lower cooling panels simultaneously through lines of equal length. Solenoid valves and manual valves were installed to provide throttling of the coolant flow and to alter the distribution as required to achieve approximately equal temperatures on the upper and lower surfaces.

The test tank was insulated to reduce heat transfer at the non-chilled surfaces. Blocks of solid polyurethane foam 57 mm. (2.2 inches) thick covered most of the exposed surfaces, and fiberglass batting filled small voids. Over the insulation, a vapor barrier of insulating paper bonded to aluminum foil

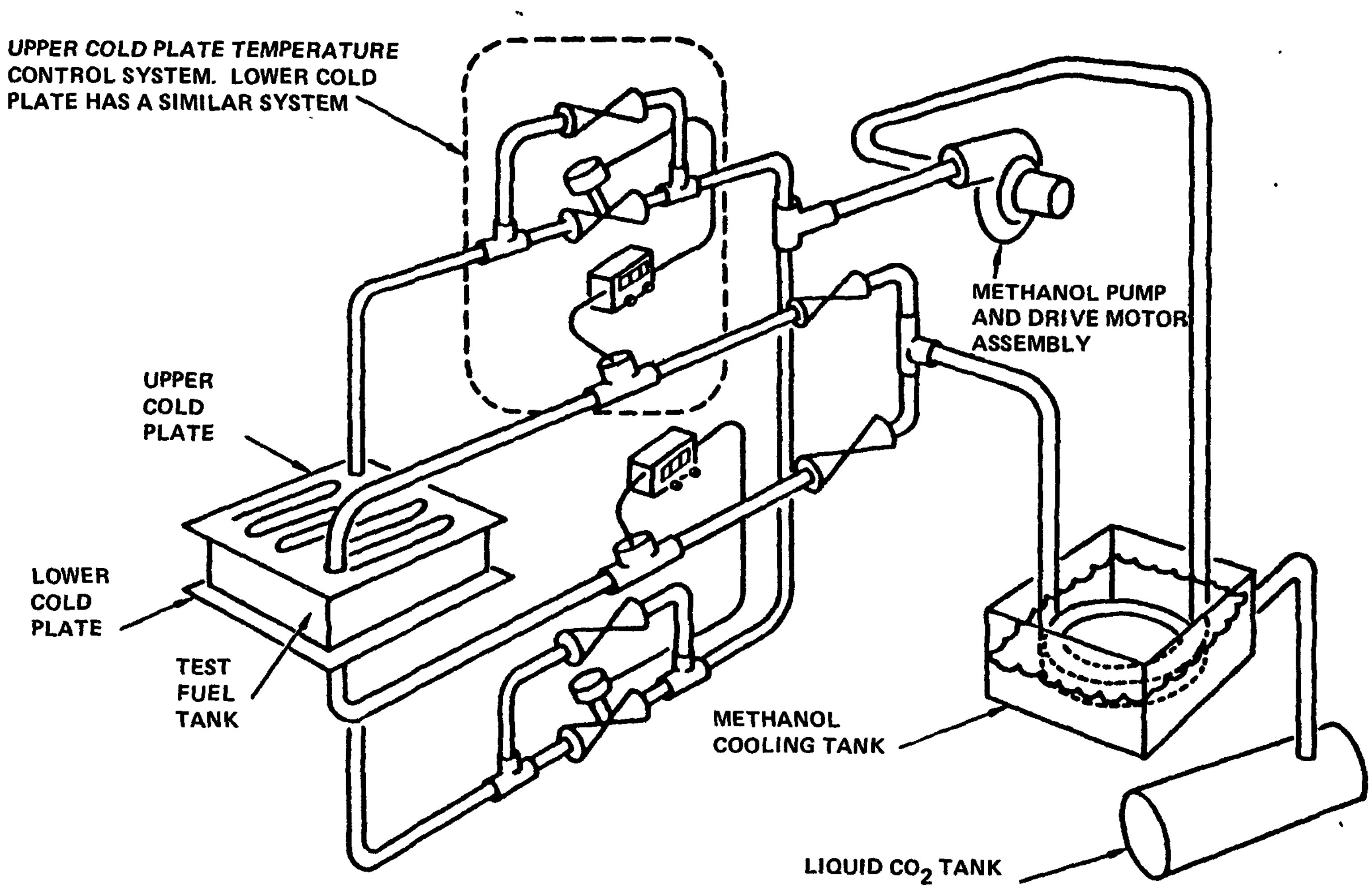


FIGURE 5 - FUEL TANK CHILLING AND TEMPERATURE CONTROL SCHEMATIC

was installed. All external lines and the boost pump chamber were insulated by appropriate combinations of fiberglass batting, polyurethane foam, and preformed foam rubber tubing jackets.

3.5 INSTRUMENTATION AND DATA ACQUISITION

An array of 55 thermocouples was used to sense temperatures inside the test tank. Thermocouples were fabricated from copper-constantan wire, and attached to five vertical rod supports inside the test tank. The beads of the thermocouples projected approximately 13 millimeters (0.5 inch) from the rods. Wire bundles from the tops of the rods were gathered to pass through a common penetration near the top of the test tank, after which a sealant was applied at the penetration to prevent fuel leakage.

Figure 6 illustrates the arrangement of these thermocouples inside the test tank. As shown, there were three thermocouple racks with 12 thermocouples each, two with seven thermocouples each, and five additional skin thermocouples. The identification and location of each thermocouple is listed in Table 1.

Calibrated venturis were used to measure fuel flow rates in the heating system and in the tank outflow line. The venturi differential pressure ports were connected to differential pressure gauges for visual reference, as well as to differential pressure transducers whose output was recorded on the data acquisition system. Oil flow rate was measured with a turbine flowmeter transmitter.

An automatic data recording system was available to acquire temperature and flow rate data. This system was compatible with the central data system at the Rye Canyon Research Center, so that tabulations of test data could be produced by computer. Further details and examples of test data printouts may be found in Reference 14.

Test data was also acquired by means other than the automatic system. Coolant temperature was monitored on a strip chart whose pens indicated temperatures at the reservoir and at the inlet to the test tank cooling panels. Fuel discharge quantity was measured by weighing fuel on a platform scale of 227 kilograms (500 pounds) capacity. On the scale platform, a clean drum was positioned to contain fuel pumped or drained from the tank. Fuel boost pump pressure was observed visually and recorded manually as required. Qualitative observations of the nature of the solid fuel buildup in the tank and other remarks were recorded in a permanent notebook for each test. Photography provided black and white prints and color slides.

3.6 FUEL HEATING SYSTEM

Fuel was heated by circulation through the tubes of a shell-and-tube heat exchanger, using MIL-L-23699 synthetic base, aviation turbine engine lubricating oil as the heat transport fluid. Figure 7 is a schematic illustrating the principal features of the system.

Fuel was pumped from the test tank by the boost pump at the controlled flow rate, through the heat exchanger, and was returned to the test tank through

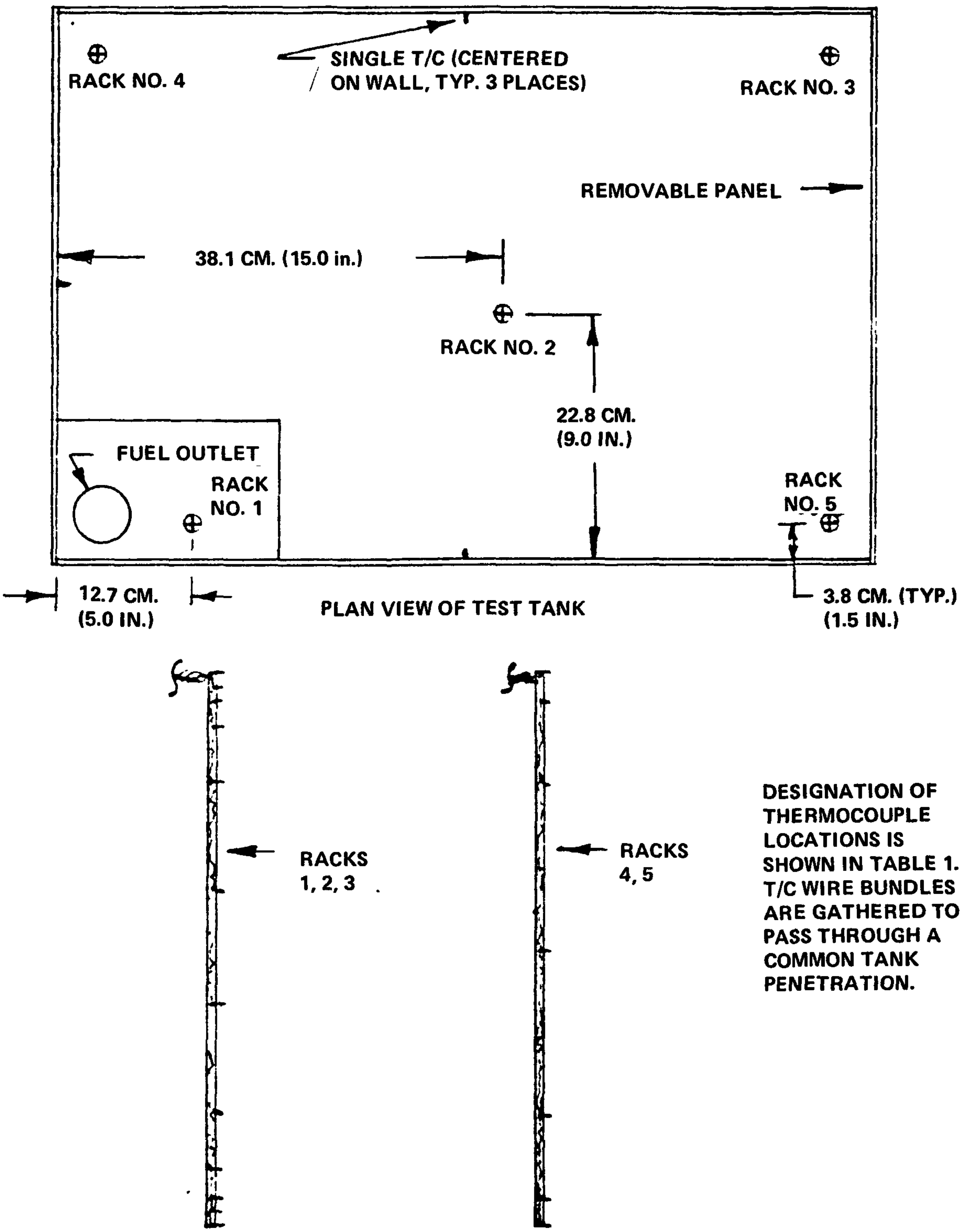


FIGURE 6 - ARRANGEMENT OF THERMOCOUPLES IN FUEL TEST TANK

TABLE 1

THERMOCOUPLE LOCATIONS INSIDE TEST TANK

Height Above Bottom Cm.	In.	Rack 1	Thermocouple Designations Rack 2	Rack 3	Rack 4	Rack 5
0	0	1	13	25	37	44
0.6	0.25	2	14	26	--	--
1.3	0.50	3	15	27	--	--
2.5	1.00	4	16	28	38	45
5.1	2.00	5	17	29	--	--
10.2	4.00	6	18	30	39	46
25.4	10.00	7	19	31	40	47
40.6	16.00	8	20	32	41	48
45.7	18.00	9	21	33	--	--
48.3	19.00	10	22	34	42	49
50.2	19.75	11	23	35	--	--
50.8	20.00	12	24	36	43	50

Thermocouples 51, 52, and 53 are centered on vertical panels.

Thermocouples 54 and 55 are located on the upper skin.

Thermocouples 56 and 57, fuel into and out of the heat exchanger.

Thermocouples 58 and 59, oil into and out of the heat exchanger.

Thermocouples 60 and 61, circulating fuel in and out of test tank.

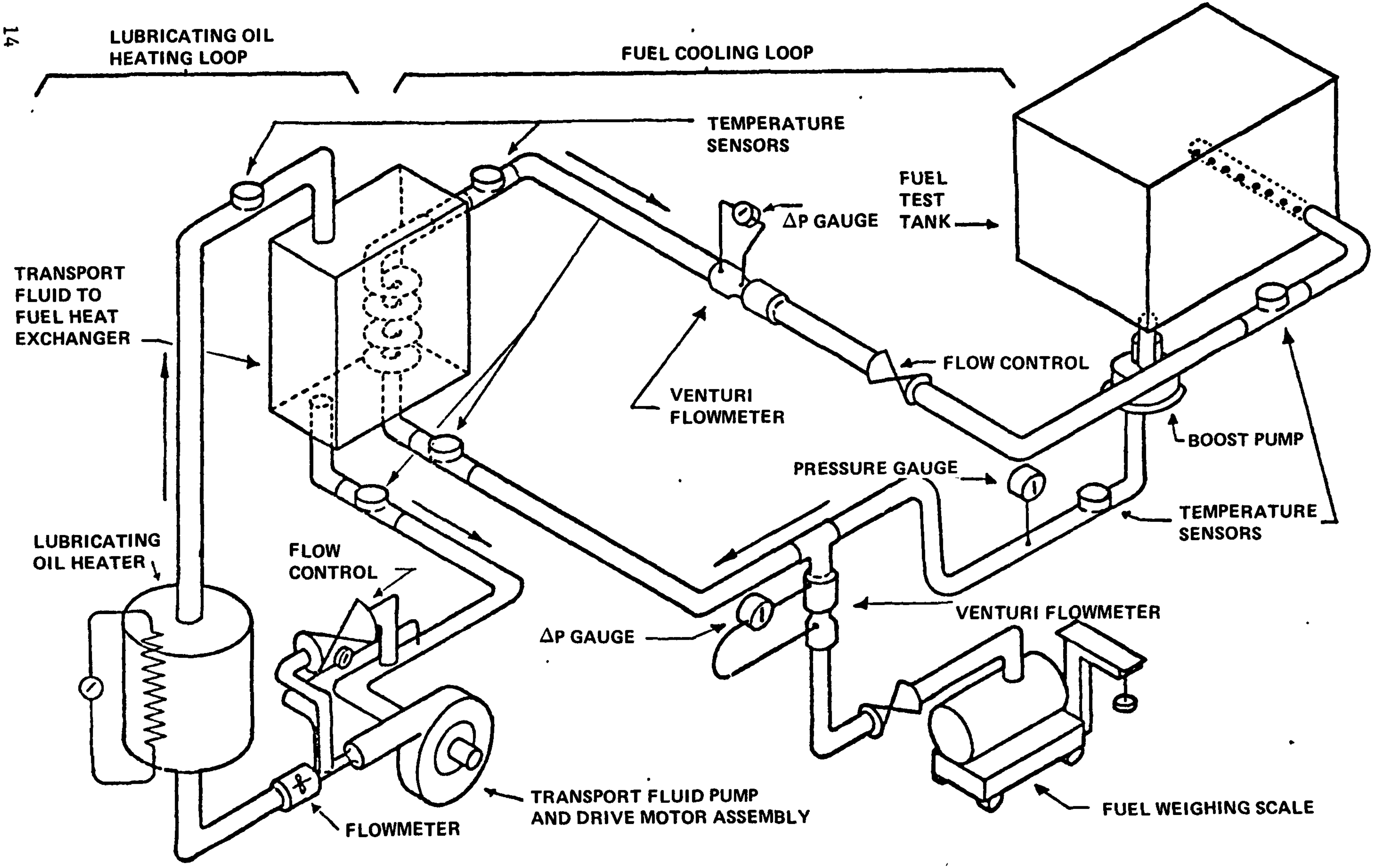


FIGURE 7 - FUEL HEATING AND TRANSPORT FLUID SYSTEM SCHEMATIC

the perforated recirculation distributor tube shown in Figures 1 and 2.

The lubricating oil transport fluid was pumped at a controlled rate through an electric immersion heater assembly, through the shell of the heat exchangers, and returned to the pump inlet. A small makeup tank (not shown on the schematic) was teed into the system to accommodate volume changes due to temperature. Heat input to the transport fluid was controlled by varying the voltage applied to the heater to obtain the desired heating rate; maximum capability of the heater was 1500 watts.

4.0 TESTING PROCEDURES

A generalized procedure for conducting tests is itemized below, followed by details pertinent to the types of tests.

- Load fuel into the test tank until liquid appears in the vent tube to insure a completely filled tank during chilldown.

- Check that the coolant in the reservoir has been chilled to the temperature required to perform the test.

- Start the data acquisition system.

- Start the coolant circulation system.

- Control the temperature of the lower and upper panels of the test tank according to the schedule appropriate for the nature of the test.

- For tests requiring heating, initiate fuel heating at the time or temperature condition selected for the test. (In most cases the heat transfer fluid was heated prior to initiating fuel flow through the heat exchanger.)

- Record data at nominal six minute intervals for the first 30 minutes, then at nominal 30 minute intervals thereafter, with additional scans at initiation of heating and pumpout.

- Continue test until a specified fuel temperature is attained for cold fuel holdup tests, or until a scheduled time period is completed.

- Pump out the fuel in the tank at nine to ten liters per minute (5% of tank capacity per minute). As the fuel level recedes to the top of the lower stringers, energize the ejectors to scavenge fuel from the bays between stringers. Record test data at initiation of pumpout and at one or more points prior to becoming empty.

- Manually record observations of tank appearance, photograph the tank interior when holdup is evident.

- Determine the weight percent of holdup.

4.1 COLD FUEL HOLDUP TESTS

These tests were performed with no recirculation or heating of fuel to obtain a range of low temperature holdup measurements analogous to those reported in Ref. 11. At the appropriate time or temperature the fuel was pumped out and weighed. The quantity by weight which did not flow by gravity to the boost pump constituted the holdup. These tests were used to characterize the low temperature behavior of each fuel.

4.2 HEATING TESTS

In contrast to the cold fuel holdup tests, which used a constant tank inner surface temperature after an initial childown period, heating tests were conducted with variable surface temperatures. Figure 8 shows the time-temperature schedules of surface temperatures used in the tests. Schedules for the extreme cold day were based on a one-day-per-year (0.3%) probability (Ref. 15). Schedule for the standard day was based on a median probability (Ref. 16). Surface temperatures for the two schedules were calculated for 90% ram recovery at 0.80 Mach flight speed at altitudes from 10.7 to 11.9 Km (35,000 to 39,000 ft.). The extreme cold day schedule corresponding to that of Ref. 15 was modified as shown in Figure 8 for better control of bulk temperature chilldown conforming to previous tests on the tank (Ref. 14). Tests were terminated at about seven hours to eliminate the warming portion of the schedule and achieve maximum holdup.

For the heating tests, fuel was recirculated by the boost pump through the fuel heating system heat exchanger, and returned to the test tank through the perforated distributor tube. Heating was regulated at several levels from a nominal 150 to 600 watts (1 to 4 watts per kilogram of tank capacity). Heating commenced after the test began, except for two tests in which heating was initiated when the thermocouple at 10.2 centimeters above the bottom of the tank, representative of bulk fuel temperature, registered $8^{\circ}C$ above the freeze point of the fuel. The heated fuel recirculation rate was approximately three liters per minute (1.5% of tank capacity per minute), and the heat transport fluid flow rate was approximately 3.8 liters per minute.

Prior to the fuel heating tests, tests were performed with the extreme cold-day surface temperature schedules without heating to establish baseline information for evaluation of the effects of heating in subsequent tests. An unheated scheduled withdrawal test was also conducted with the LFP-14 fuel. This test, corresponding to those reported previously (Ref. 11), involved an 11.3 hour duration extreme cold day schedule with fuel withdrawal at 1 liter/min. during the last three hours of the test. This simulated a long-range flight with fuel utilization from an outboard reserve tank during the latter portion of cruise. The same fuel was also tested for typical behavior by an unheated test at the standard day skin temperature schedule (Fig. 8).

Three configurations for the fuel recirculation distributor tube were tested:

- o Short perforated tubes perpendicular to the tank stringers, supplied from a larger tube, and positioned close to the tank bottom
- o One tube with a single row of holes, positioned above and perpendicular to the stringers.
- o Perforated tubes parallel to the tank stringers, supplied from a larger tube, and positioned close to the tank bottom.

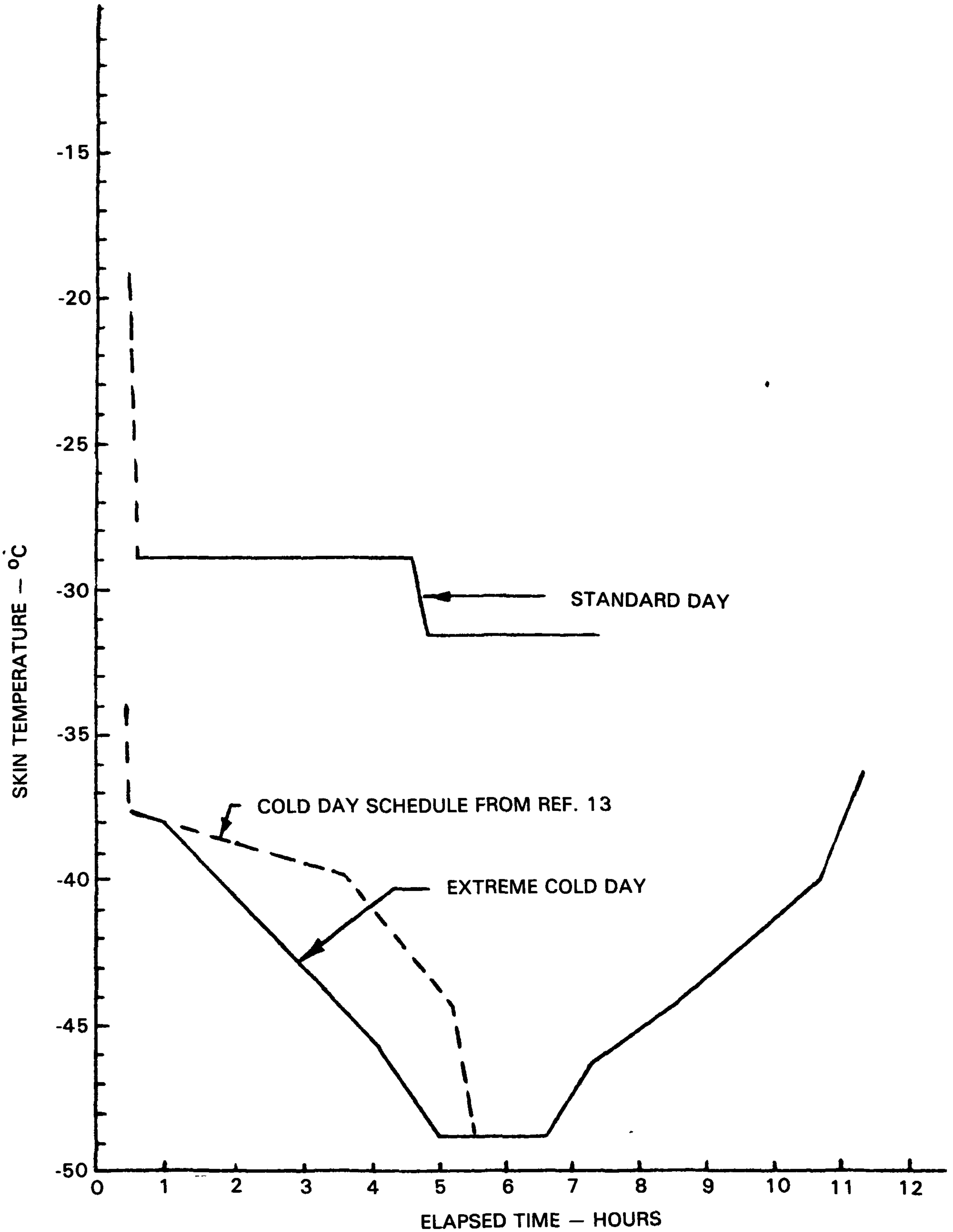


Figure 8 — Test Tank Skin Temperature Schedules

4.3 FLOW IMPROVER ADDITIVE TESTS

Three flow improver additives were obtained from the Paramins organization of Exxon Chemical Company. These were used to treat the higher-freezing-point fuel (LFP-14) and two other experimental fuels (LFP-5 and LFP-6) at concentrations of 1000 parts per million (0.10%) by weight. They were also used to treat the low-freezing-point fuels (LFP-1 and LFP-15) at concentrations of 500 parts per million. For each of these fuels, cold fuel holdup tests were performed with untreated and treated fuel. The LFP-14 fuel, with and without additive, was also tested according to the extreme cold day temperature schedule.

At the end of each set of tests using a particular fuel and flow improver additive, the fuel tank and its related equipment, (filters, weigh barrel, etc,) were drained and flushed with Jet-A prior to further testing. This was done to insure that no significant remnants of additive doped fuel could mix with other neat or doped fuels.

5.0 FUELS

The principal fuel used in the test program was:

- LFP-14, an experimental kerosene fuel blend with an increased freezing point of $-33^{\circ}C$, but otherwise conforming to the specifications of commercial aviation turbine fuel Jet A.

Some tests were conducted with two other fuels used in the previous test program (Ref. 11):

- LFP-5, an experimental paraffinic fuel with a freezing point of $-28^{\circ}C$, derived from a refinery distillate stream.
- LFP-6, an experimental naphthenic fuel with a freezing point of $-29^{\circ}C$, derived from a refinery distillate stream.

Limited tests with flow-improver additives were conducted with two conventional freezing point aviation turbine fuels as well:

- LFP-1, a paraffinic Jet A used in the earlier test program (Ref. 11), with a $-42^{\circ}C$ freezing point.
- LFP-15, a 70/30 blend of JP-5 and JP-8 obtained from the Air Force Wright Aeronautical Laboratories, with a $-50.6^{\circ}C$ freezing point.

Figure 9 shows distillation characteristics of the five test fuels. Table 2 is a list of selected characteristics and test methods for the fuels.

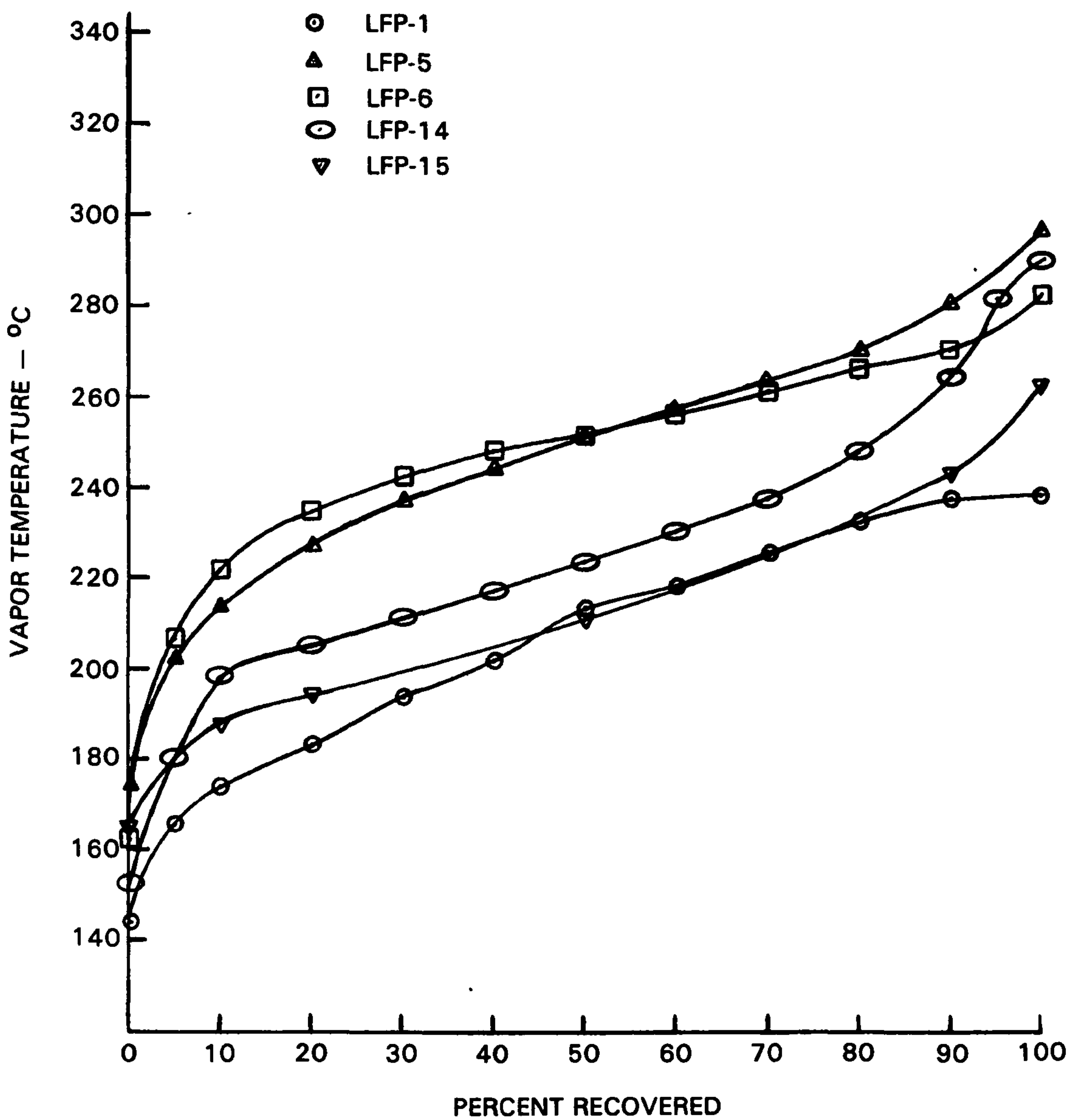


Figure 9 — Distillation Characteristics of Test Fuels, ASTM Method D-86 (Ref. 7)

TABLE 2

CHARACTERISTICS OF TEST FUELS

	LFP-1		LFP-5		LFP-6		LFP-14		LFP-15	
Specific Gravity	0.8017		0.8299		0.8478		0.8079		0.8067	
Water KF D1744	-		-		-		80 ppm		-	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F
Freeze Point D2386	-42	-43.6	-28.0	-18.4	-29	-20.2	-33	-27.4	-50.6	-59
Pour Point D97	-50	-58.0	-31.0	-23.8	-32	-25.6	-35	-31.0	-	-
DISTILLATION D86										
Initial Boiling Point	142.2	288	173.9	345	162.2	324	152.2	306	165.0	329
5%	165.6	330	202.2	396	206.7	404	180.0	356	-	-
10%	173.3	344	213.3	416	221.1	430	197.8	388	187.8	370
20%	183.3	362	227.2	441	234.4	454	205.0	401	194.4	382
30%	193.3	380	236.7	458	242.2	468	211.1	412	200.0	392
40%	201.7	395	243.9	471	247.8	478	216.7	422	205.6	402
50%	213.3	416	251.1	484	251.7	485	223.3	434	211.1	412
60%	217.8	424	256.7	494	256.1	493	230.0	446	217.2	423
70%	225.0	437	263.3	506	261.1	502	237.2	459	223.3	434
80%	232.2	450	270.0	518	266.1	511	247.8	478	231.7	449
90%	237.2	459	280.6	537	271.1	520	264.4	508	243.3	470
95%	-	-	-	-	-	-	281.7	539	-	-
End Point,	237.8	460	296.7	566	282.8	541	290.0	554	262.2	504

6.0 RESULTS

This section of the report presents a summary of the tests, grouped, for the most part, in accordance with the types of tests described in the section on test procedures. A chronological itemization of all test runs may be found in Appendix A, which is a table listing the test number, date, fuel, heating and test variables, holdup results, and remarks. Testing commenced on 23 July 1981.

6.1 COLD FUEL HOLDUP TESTS

Cold fuel holdup tests were used to characterize the low temperature behavior of each fuel in terms of the relationship of holdup (the unpumpable fuel remaining in the tank), and fuel temperature.

Figure 10 is a photograph of the interior of the tank after pumpout in Test 203, which produced 5.00% holdup. Previous testing (Ref. 11) had shown that at least 3% holdup was required to coat the tops of the stringers, after which the solid deposits deepened on the bottom and thickened on the stringers. Texture of the deposits is fairly smooth with a waxy appearing surface. Depressions formed in the holdup under the ejectors when they were operated as slush was pumped out.

A series of cold fuel holdup tests were conducted over a range of pumpout temperatures, in order to characterize the flowability behavior of the LFP-14 fuel.

Figure 11 summarizes the fuel temperature environment for this series of tests by plotting the temperature gradients in the center of the tank at initiation of pumpout, corresponding to several amounts of holdup. Only the lower portion of the tank is shown. Because of convection currents, readily observable, solid deposits were confined to the lower surfaces. The entire temperature profiles were somewhat symmetrical except that the upper gradients were narrower than those shown for the lower surface.

Figure 11 also shows the freezing and pour points by broken lines. In all but the two highest holdup tests, the bulk of the fuel is above the pour point. However, some or all of the boundary layer near the bottom surface is below the pour point for all the tests. The coldest tests had the bulk fuel at or below the pour point, yet most of the fuel was pumpable (23% holdup).

The photograph in Figure 10 shows the height indicator in the center of the simulator tank, which served to estimate the height of the layer of solid or slush fuel remaining in the tank after pumpout. These heights are indicated on the Figure 11 temperature gradients. Note that the solid-liquid interface heights occur near, and generally within 2°C, of the pour point.

6.2 HEATING TESTS

A baseline, unheated test was conducted according to the extreme cold day schedule shown in Figure 8, prior to the heating tests. Temperature profiles, temperature histories, and holdup were measured to serve as a reference for subsequent heating tests. Figure 12 shows the baseline time histories of fuel

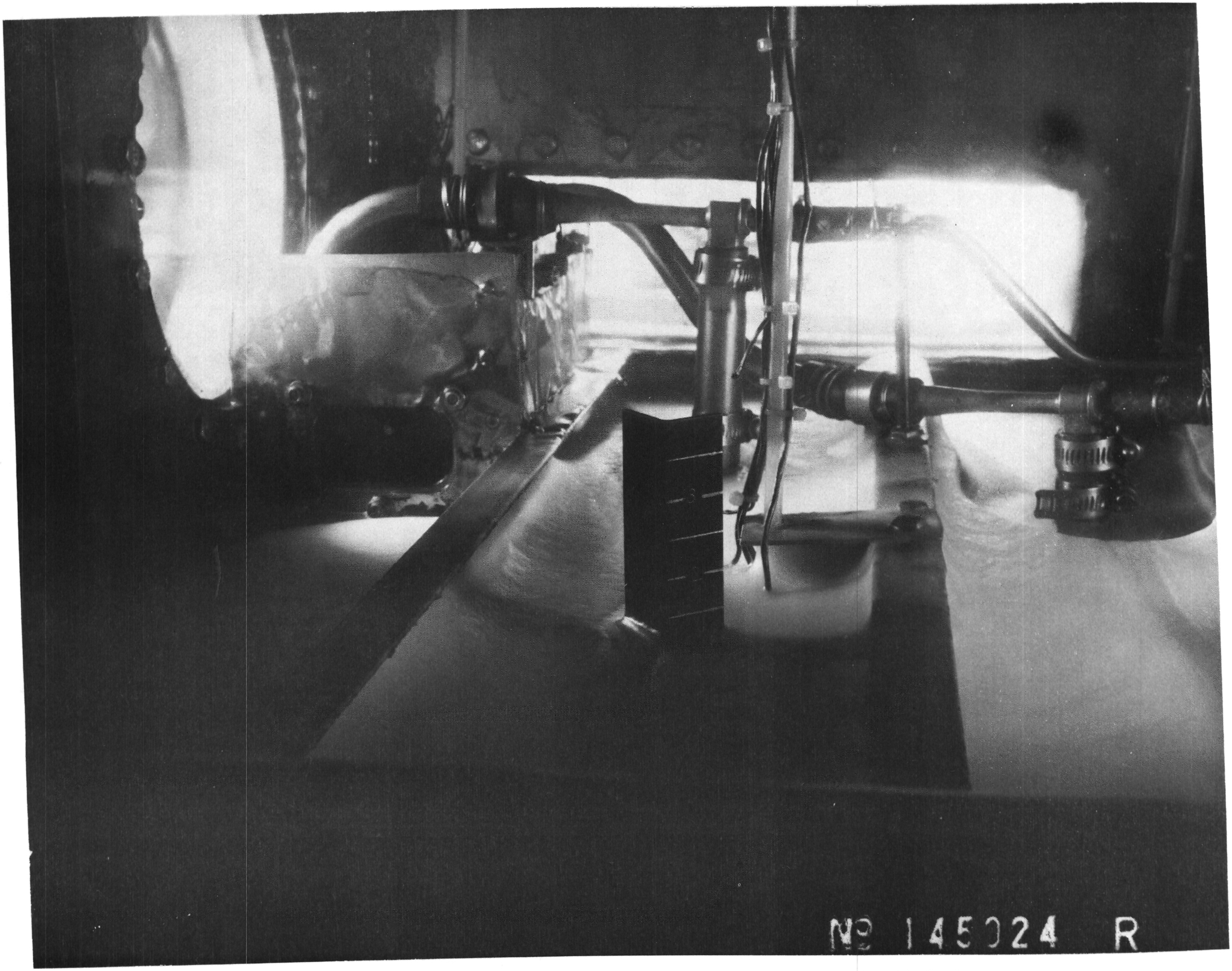


FIGURE 10 - Tank Interior for Test 203, 5.00% holdup, LFP-14 fuel.

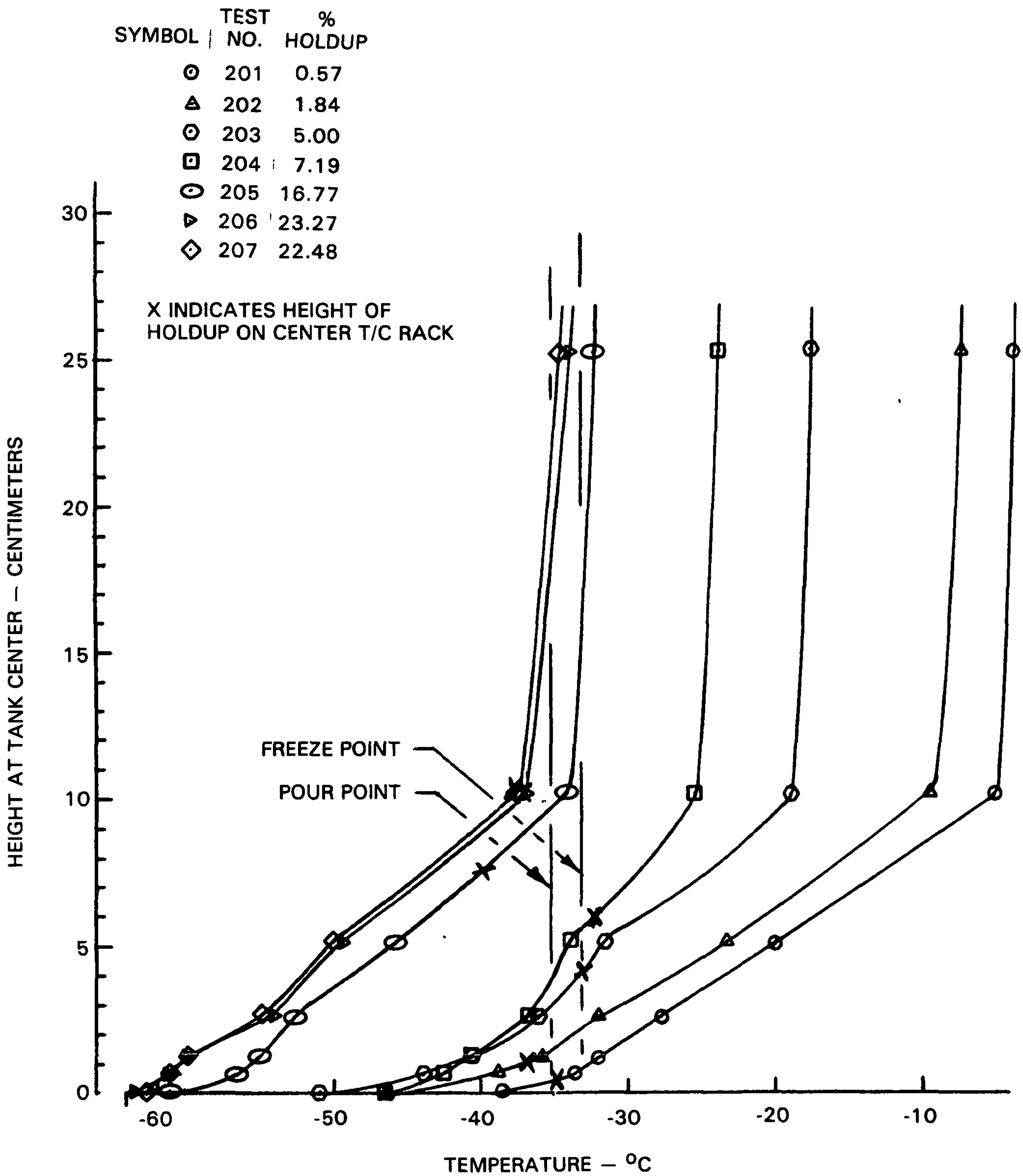


Figure 11 — Temperature Gradients For Cold Fuel Holdup Tests, LFP-14 Fuel

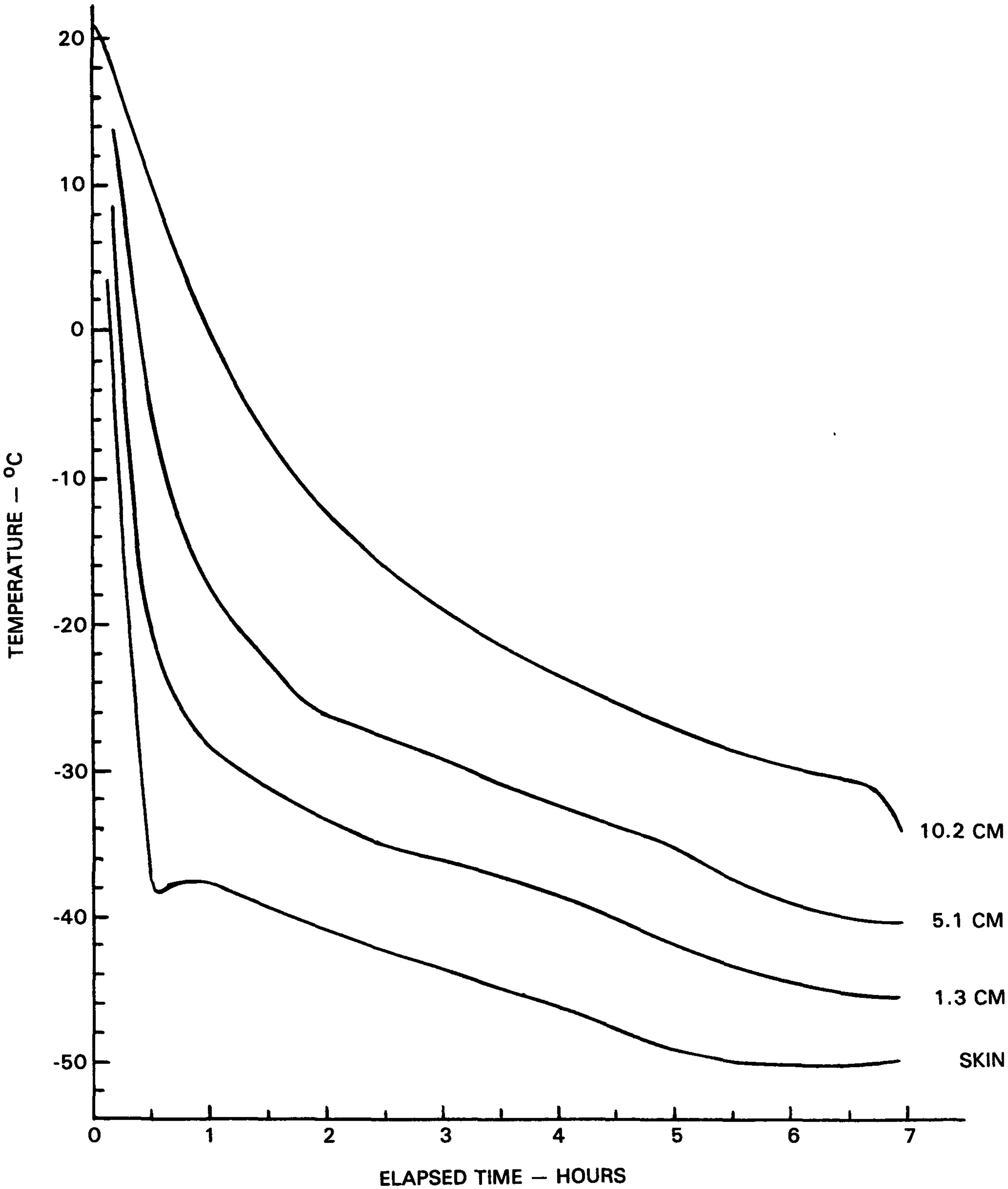


Figure 12 — Time History, Extreme Cold Day Schedule, No Heating, Test 210, LFP-14 Fuel

temperatures at the center of the tank for the bottom skin and several heights above the bottom. The 10.2 cm reading is, for practical purposes, that of the bulk fuel (Figure 11). Holdup for this baseline test was 8.76%. Another unheated, baseline test, not plotted here, was conducted at the standard day schedule of Figure 8. There was no holdup for this test, indicating that LFP-14 fuel would have pumpability problems only for environments more severe than those of a standard day.

Figure 13 shows the time history of fuel temperature at the center of the tank for a test at the same skin temperature schedule as the cold-day baseline, but with fuel heating initiated 4.2 hours after the test start. Heating rate was a nominal 150 watts. However, the lubricating oil was heated from the start of the test and the fuel heating was non-uniform when recirculation was started, high initially and then tapering off. The effect of heating is seen to be rapid and large at the 5.1 and 10.2 cm locations and much less at 1.3 cm, near the bottom skin. Holdup was reduced to 2.37%.

Figure 14 shows the results of a test where fuel heating was continuous, starting with the beginning of the test. Heating rate was a nominal 150 watts. The temperatures decreased throughout the test, but to a lesser extent than those of the baseline test (compare Figure 12). Holdup was reduced to 3.05%.

The two methods of heating produced similar temperature profiles. However, the measured holdup and height of solids indicate some advantage to storing energy in the oil and heating the fuel from later in the test at essentially a higher rate.

Tests were also conducted with higher rates of heating than illustrated in Figure 14. Figure 15 shows tank center temperatures for a test with the cold-day skin temperature schedule, but a nominal 300 watt heating rate. The history resembles that of Figure 14, but temperature levels are increased, particularly for the bulk fuel. Holdup was reduced further to 2.27%

In summary, from a series of tests with the same fuel and heating method, holdup was seen to decrease from 8.76% for no heating, to 3.05%, 2.27%, and 2.22% for continuous heating rates of nominal 150, 300, and 600 watts. Most of the benefits of heating occur at low heating rates. Since reference to the extreme cold day schedule requires low skin temperatures, some sub-freezing fuel is always to be expected near the chilled surfaces. Thus, high heating rates are ineffective in completely reducing holdup to zero.

Three configurations for the recirculation distributor tubes were tested; Figure 16 presents photographs of these assemblies. The single row recirculation distributor was a 3.2 cm (1.25 in.) outside diameter tube extending across the tank with 34 holes, of 0.63 cm. (0.25 in.) diameter, aimed at the opposite, pump inlet end of the tank (Figure 2). The low re-entry cross flow recirculation distributor had the same number and size of holes, but they were located on extensions fitted between the tank bottom stringers. Both these designs were used in the earlier fuel heating tests described in the Volume I report (Ref. 14). The low re-entry cross flow distributor was used for the baseline and most of the heating tests. The

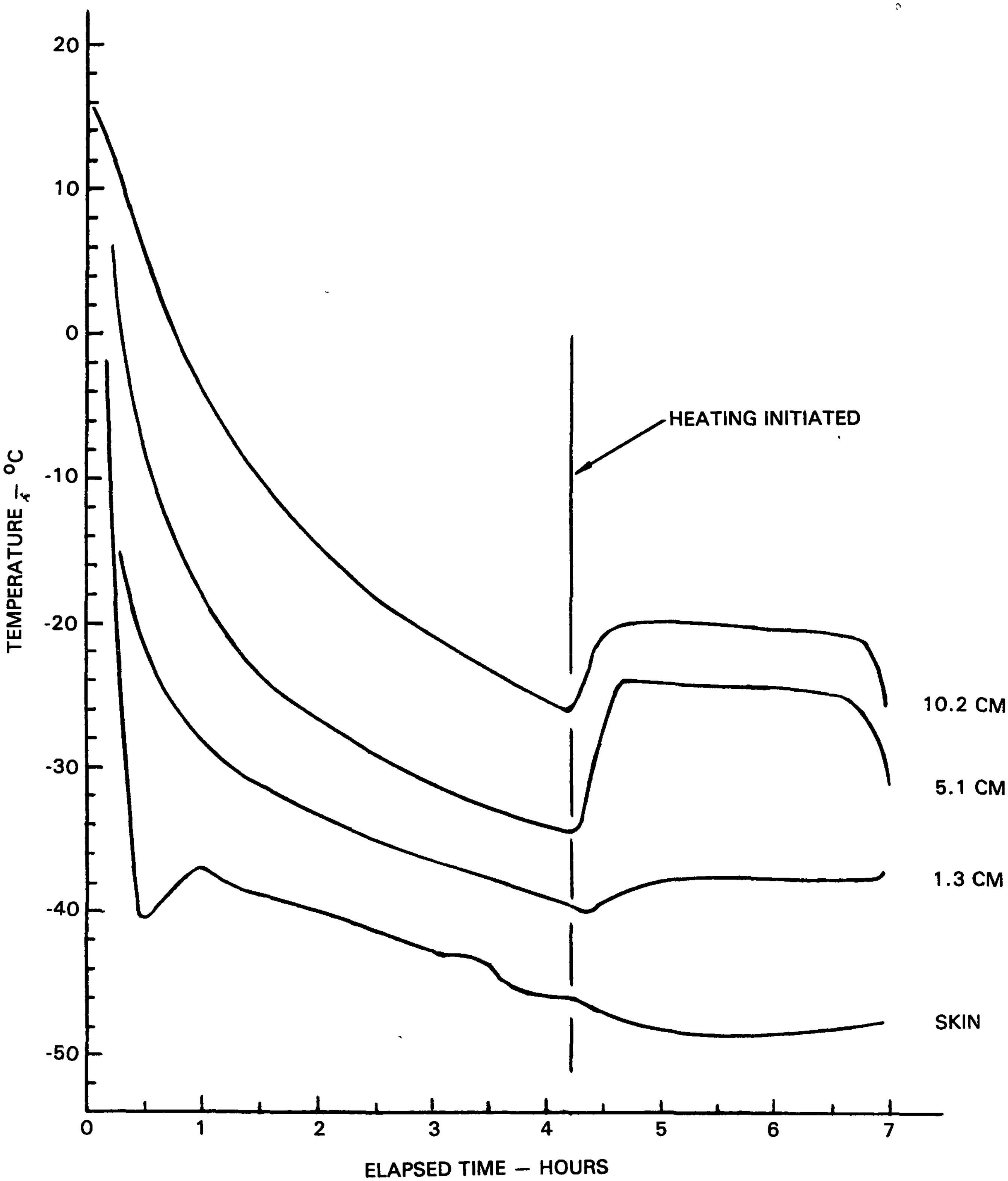


Figure 13 — Time History, 150 Watt Nominal Heating Initiated at 4.2 Hours, Test 211, LFP-14 Fuel

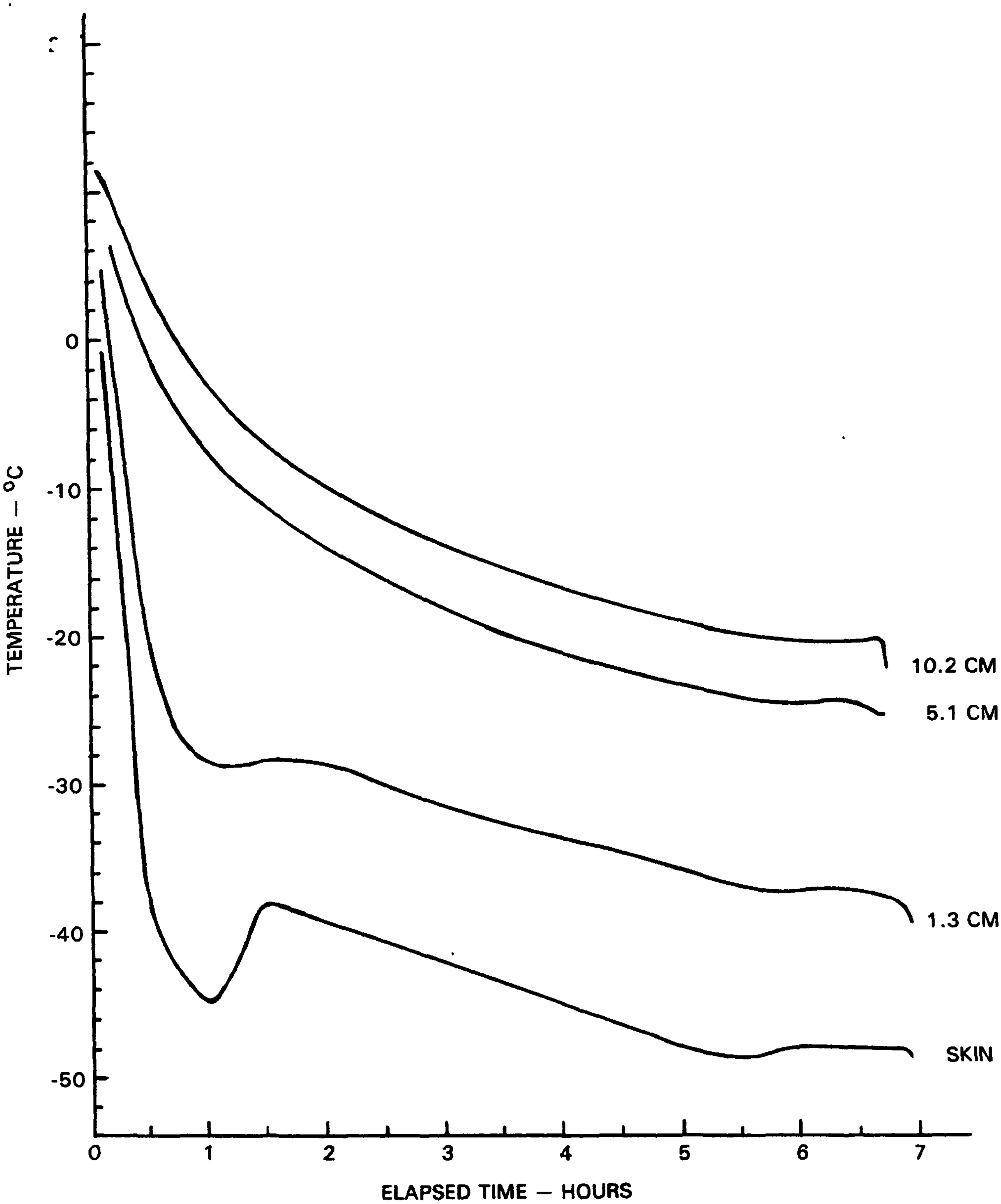


Figure 14 — Time History, 150 Watt Nominal Heating Continuous From Test Start, Test 215, LFP-14 Fuel

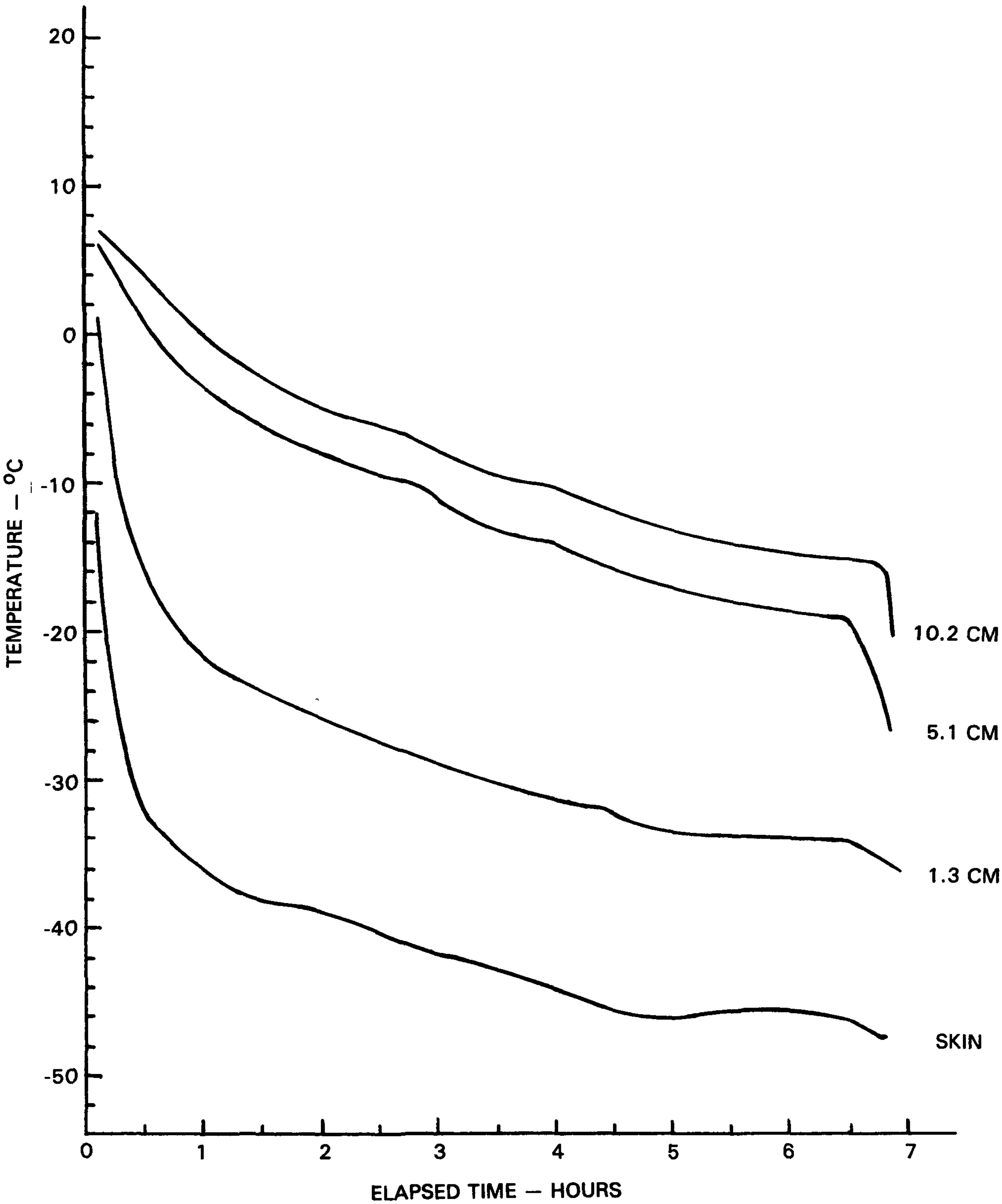
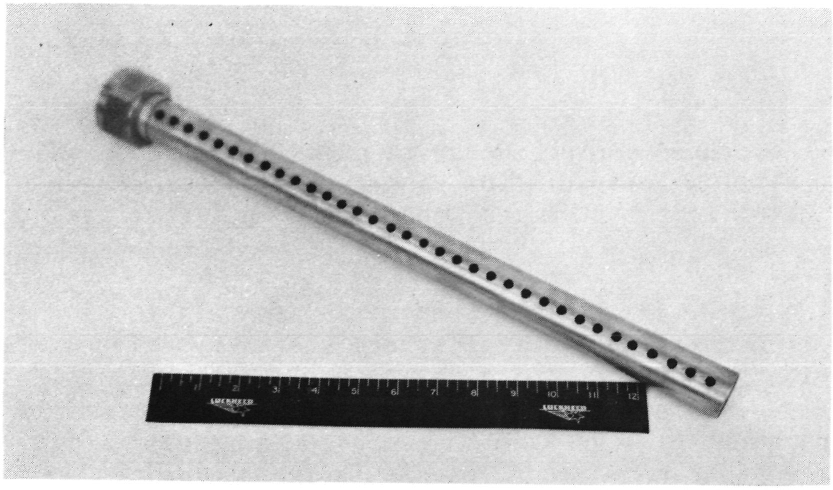
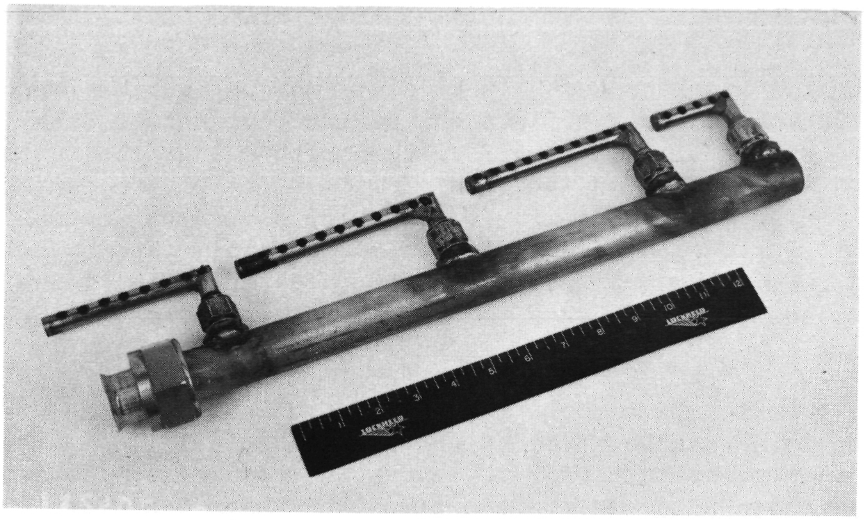


Figure 15 — Time History, 300 Watt Nominal Heating Continuous From Test Start, Test 216, LPF-14 Fuel



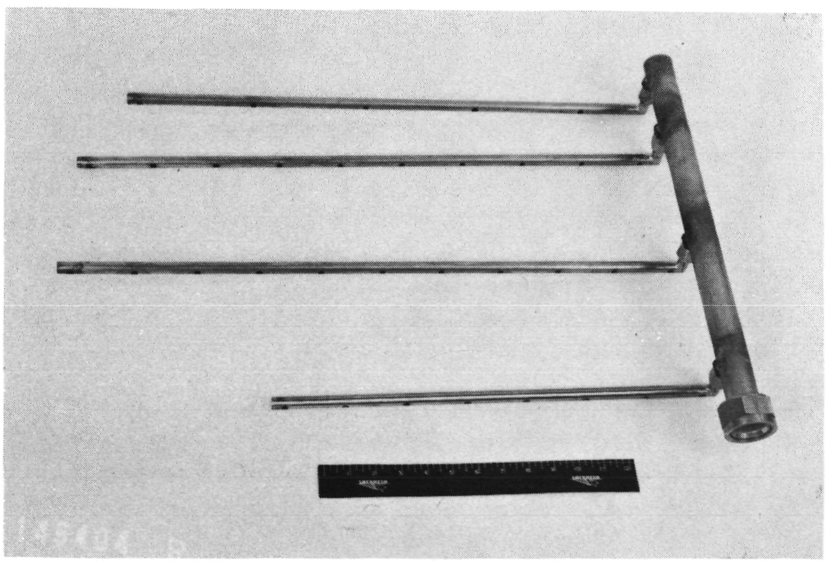
SINGLE ROW

RECIRCULATION DISTRIBUTOR



LOW RE-ENTRY CROSS FLOW

RECIRCULATION DISTRIBUTOR



LOW RE-ENTRY PARALLEL FLOW

RECIRCULATION DISTRIBUTOR

FIGURE 16 - RECIRCULATION DISTRIBUTOR TUBES

third design, introduced during the tests described herein, was the low re-entry parallel flow recirculation distributor. This design had the tube extensions parallel to the stringers and extending toward the pump inlet end of the tank.

Previous testing (Ref. 14) had shown that, in general, those changes which aided the penetration of heated fuel toward the tank surface, that is, the low re-entry distributor designs, could make a small but measurable improvement in the holdup. However, the low re-entry parallel flow recirculation distributor yielded holdups about 0.3% greater than for corresponding tests with the other designs. Observations showed that precipitating solids tended to accumulate and clog the holes of this distributor, directing the flow away from the surge box and bottom surface.

6.3 FLOW IMPROVER ADDITIVE TESTS

Twelve tests (plus baseline tests) were performed using flow improving additives to determine their effects on the low temperature behavior of aviation fuels with a wide range of low temperature characteristics (freeze point, pour point). The flow improver additives are proprietary polymeric materials which disperse the solid fuel particles, preventing solid coagulation and buildup. These additives are commonly used for winter service of diesel and fuel oils, but they are often quite specific in their effect on various fuels, and presently they are not on the approved additive list for jet fuels.

Table 3 gives pour point and doping concentration data for the five fuels tested. These data were obtained by the Exxon Chemical Co. laboratories using the standard pour point test (ASTM D-97). The treat rates identified by asterisks were those selected for the simulator tests described in this report. The three higher freezing point fuels, LFP-5, LFP-6, and LFP-14, all responded well in the laboratory evaluation. One conventional freezing point fuel, LFP-15, was tested briefly; the other, LFP-1, not at all. The 500 ppm treat rates for the simulator tests for these fuels were suggested by the manufacturer, based on overall experience.

Results of the flow improver additive tests are summarized in Table 4. For the LFP-14 higher freezing point fuel, the temperature profile that yielded 16.77% holdup with neat fuel had 6.65% holdup when doped. The holdup in shorter tests where there were less solids in the baseline also had reductions in holdup on the order of 50%. At very small holdups (1%) the effect of the additive was minimal. Figure 17 shows the vertical temperature profiles at the center rack for two tests where the additive reduced holdup from 16.77% to 6.65%. Since the profiles are essentially the same, the reduction in holdup is due to a change in the fuel's low temperature flowability.

Tests with LFP-5 (-28°C freeze point) reduced holdup from 6.71% to 4.64% for the same temperature profile. Using LFP-6 (-29°C freeze point) holdup was reduced from 6.63% to 4.29% when tested under otherwise similar conditions.

TABLE 3

LABORATORY EVALUATION OF FLOW IMPROVER ADDITIVES

FUEL	ADDITIVE	TREAT RATE (PPM BY WEIGHT)	ASTM POUR POINT, °C
LFP-1	None	0	-50
	NBR 8105-153	500 *	
LFP-5	None	0	-30
	NBR 8105-151	100	-30
		200	-30
		400	-30
		600	-30
		800	-42
		1000 *	-42
LFP-6	None	0	-30
	NBR 8105-152	400	-30
		600	-42
		800	-42
		1000 *	-45
LFP-14	None	0	-33
	NBR 8105-153	100	-33
		200	-33
		400	-36
		600	-39
		800	-42
		1000 *	-42
LFP-15	None	0	-
	NBR 8105-152	500 *	6°C Decrease

* Treat rate selected for simulator tests.

TABLE 4

SUMMARY RESULTS OF FLOW IMPROVER ADDITIVE TESTS

FUEL	UNMODIFIED TEMPERATURE AT 0.6cm, °C	UNMODIFIED HOLDUP	WITH ADDITIVE TEMPERATURE AT 0.6cm, °C	WITH ADDITIVE HOLDUP
LFP-14	-56.4	16.77%	-53.4	6.65%
LFP-14	-46.9	8.76%	-43.7	2.28%
LFP-14	-43.2	5.00%	-43.5	1.53%
LFP-6	-40.8	6.63%	-41.8	4.29%
LFP-5	-41.9	6.71%	-41.5	4.64%
LFP-15	-58.9	4.94%	-58.8	4.93%
LFP-1	-48.5	6.50%	-48.0	5.93%

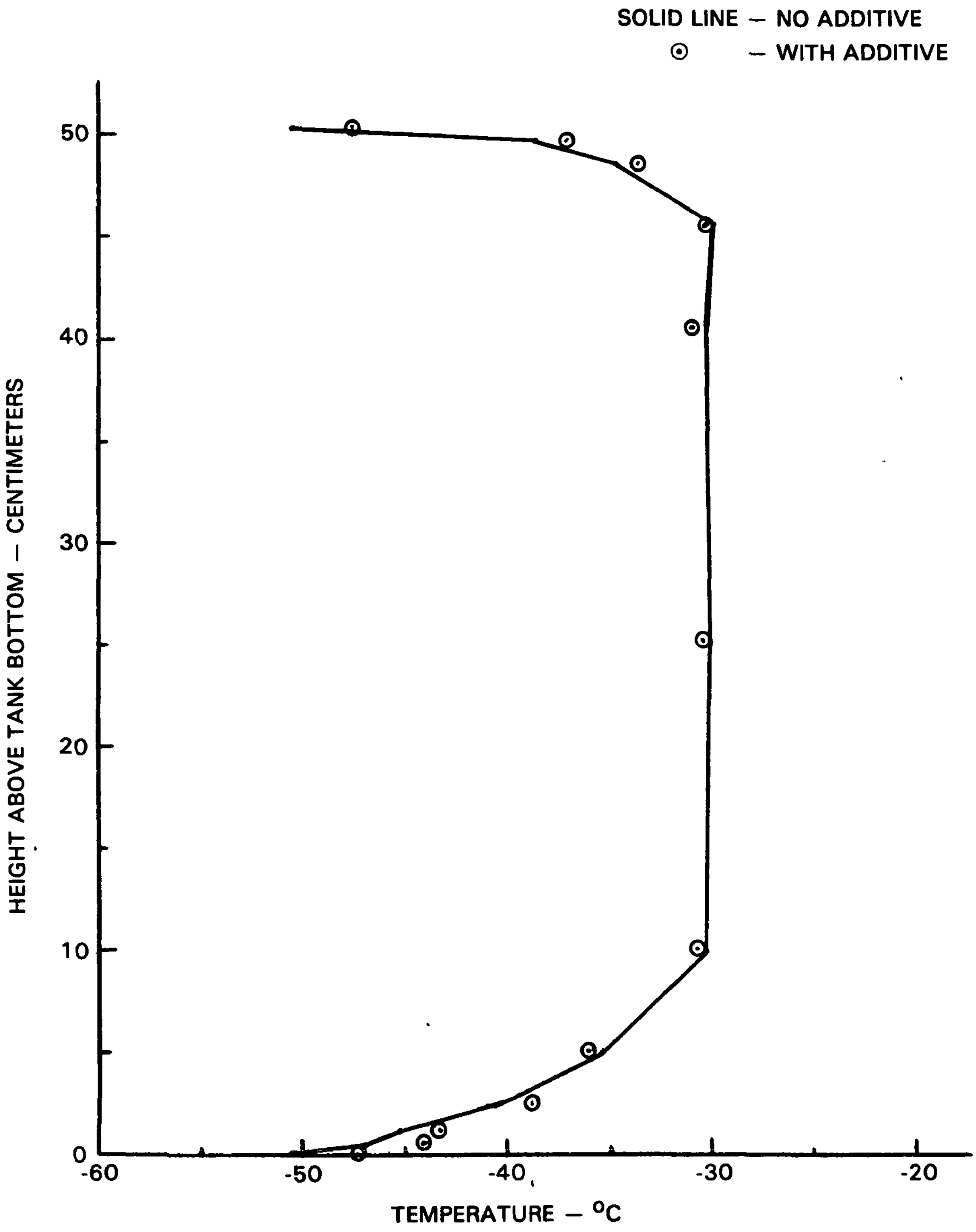


Figure 17 — Temperatures Gradients For Cold Fuel Holdup Tests, LFP-14 With and Without Flow Improver Additive

These neat fuel conditions were chosen to duplicate previous tests with the fuels, and tests conducted over two years apart agreed to within 0.1% holdup. Improvements from using additives with the conventional freezing point fuels LFP-1 and LFP-15 were very small. However, the evaluation of the additives for these fuels was very limited in scope.

7.0 DISCUSSION

7.1 VISUAL OBSERVATION OF HOLDUP

During this test program, as well as during the previous Lockheed programs (Ref. 11 and 14), visual observations proved to be an important means of data acquisition, both for interpreting data gathered through instrumentation and for understanding the process of formation and deposition of solids as described below.

Most of the fuels became cloudy during the chilldown process, and eventually limited visibility to a few centimeters. However, during an earlier test program (Ref. 11) one of the fuels remained sufficiently clear that the buildup process could be observed for a test which produced 3.6% holdup. The process for larger holdups is inferred from the distribution of holdup after pumpout.

As the upper and lower surfaces are cooled, heat is transferred from the fuel to the coolant. In particular, fuel cooled by the upper surface becomes more dense; the resultant density gradients set up a convective flow of dense, colder fuel toward the bottom of the tank. As profiles are fully developed in the completely filled tank, the center of the tank has a well-mixed uniform temperature, with gradients to the skin temperature over a considerably greater distance at the bottom compared to the top. Precipitation of solid fuel during the chilling is also influenced by the convection currents set up by the density gradients. The first visual evidence of solids is a dulling of the lower surface of the tank. As cooling continues, the dull area spreads along the bottom, then commences to climb the vertical webs of the lower stringers and later to spread across the upper horizontal flanges of the stringers. During this process, the dulling becomes identifiable as solid deposits increasing in depth on the bottom and to a lesser extent on the stringers. Eventually, the deposits form on the upper surfaces and vertical panels.

For holdups near 1%, deposits observed after pumpout were on the bottom skin only, between the lower stringers. Figure 18 shows a 1.64% holdup with LFP-5 higher freezing point fuel modified with a flow improver additive. It can be seen that solids are confined mainly to the bottom surface. Some slush had been drawn up through the ejectors.

For tests at temperature conditions producing up to 4% holdup, a thin film had covered the vertical webs and upper flanges of the lower stringers (Figure 10), and at about 6% holdup conditions, a very slight film was observed on the upper surfaces. At large holdup conditions after pumpout, solid fuel covers all tank surfaces and the surge box exterior (Figure 19). There are also solids in the surge box, but a cavity leads to the fuel pump inlet screen. No liquid holdup was evident in this case, therefore some liquid permeated through the "solids" to enter the surge box.

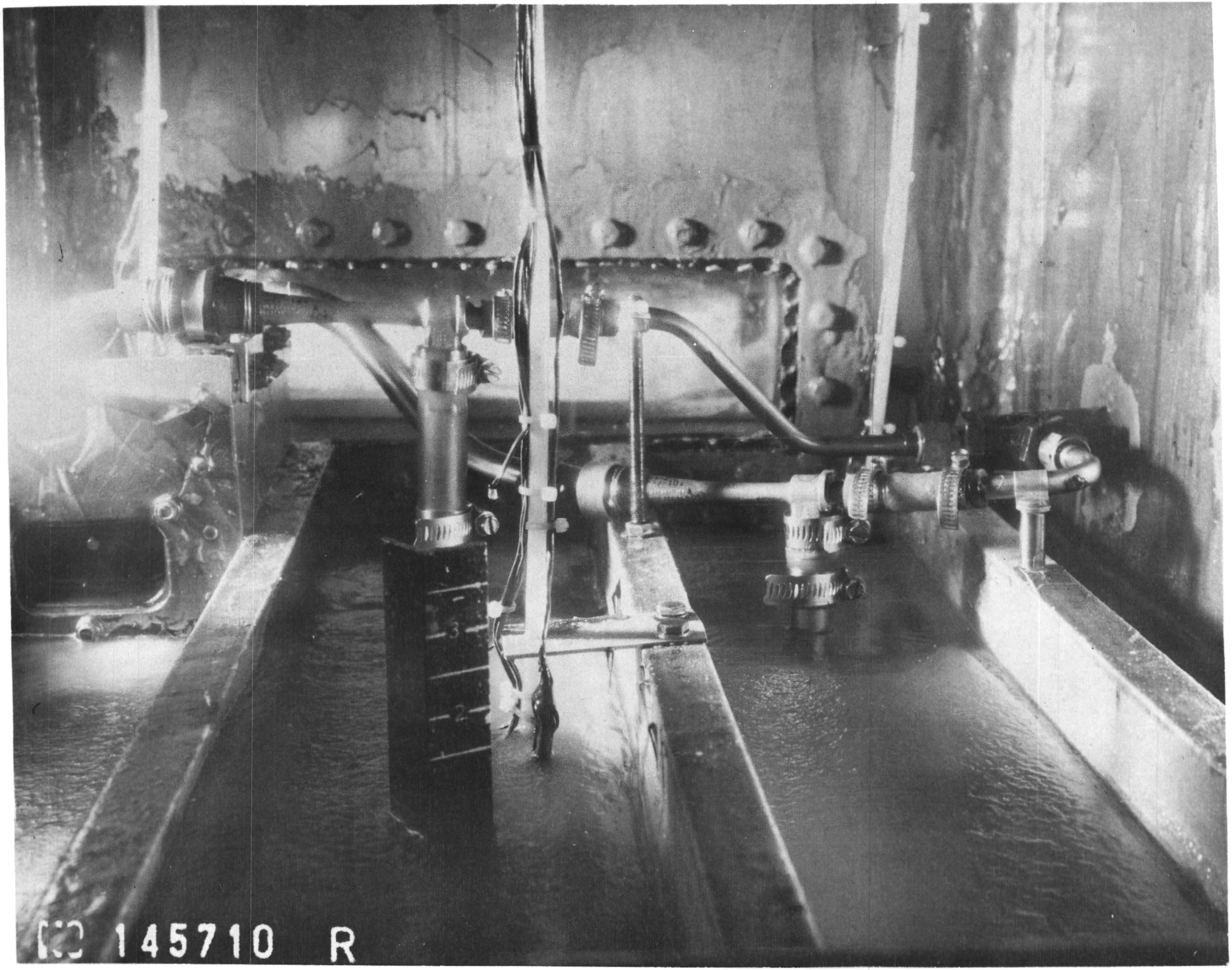


FIGURE 18. - [illegible] 1.64% [illegible] 236 LER-F FUEL PLUG FLOW IMPROVEMENT [illegible]

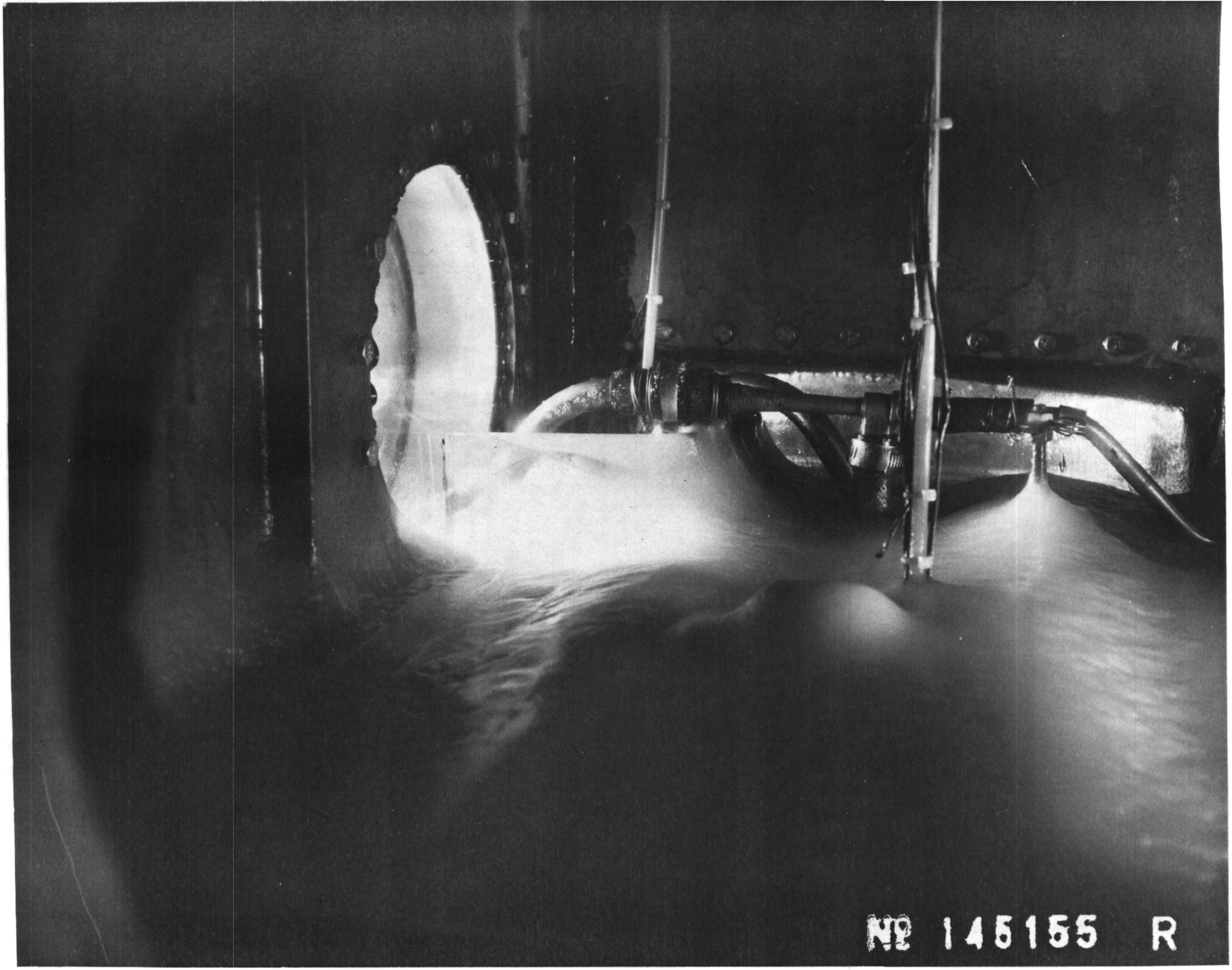


FIGURE 19 - HOLDUP OF 22.48% TEST 205, LFP-14 FUEL

7.2 TANK TEMPERATURE PROFILES

The temperature profiles presented in the Results section of this report, Figure 11 for example, have shown only the temperatures measured in the lower portion of the center of the tank. These profiles emphasize the temperature gradients in the bottom boundary layer where the solid accumulation and subsequent holdup occurred.

Two complete vertical temperature profiles are illustrated in Figure 20. These temperatures were measured at the center of the tank for the higher freezing-point fuel LFP-14, prior to pumpout after testing with the extreme cold-day skin temperature schedule. The vertical temperature profiles are for tests with no heating, and with nominal 300 watt heating from the start of the test. Temperature histories for these two tests are shown in Figures 12 and 15 respectively. The effect of heating is most evident in the increase in the bulk temperature of about 15°C. In both cases, convection causes a narrow boundary layer at the top, as compared to the wider one at the bottom. Eddies within the fuel were frequently visible during the more rapid cooldown portions of the unheated tests. During heating, the hot recirculating fuel could be seen to start rising as soon as it exited the flow distributor.

The complete temperature measurements for the two cases illustrated in Figure 20 are listed in the following two tables. Thermocouple rack locations are defined in Figure 6. Table 5 shows the horizontal temperature distribution throughout the tank just prior to pumpout for the unheated case. The largest deviation from horizonatal uniformity is at the lower location of Rack 1, probably caused by its proximity to the surge box and pump inlet.

Table 6 shows the horizontal temperature distribution throughout the tank just prior to pumpout for the heated case. The bulk fuel is well mixed, as evidenced by the uniform warm temperatures throughout the table at heights between 5 and 50 centimeters. The test used for reference had the low re-entry cross flow recirculation distributor (Figure 16). At heights of 1.3 to 5 cm, the circulation path is apparent, as warm temperatures are noted at thermocouple racks 3 and 5 at the corners nearest the distributor. The center (Rack 2) and opposite corner (Rack 4) are cold at these levels. Tests with the single row distributor showed slightly exaggerated temperature differences near the bottom, suggesting poorer penetration. Tests with the low re-entry parallel flow distributor gave temperature distributions nearly equal to those with the cross flow distributor. It was originally felt that the latter distributor would improve penetration by introducing the heated fuel near the bottom throughout the tank. However, some evidence indicated that clogging of some of the distributor holes by fuel solids inhibited the parallel flow distributor from operating efficiently. These results do suggest that increasing the velocity of the fuel as it leaves the distributor may keep the fuel closer to the floor for a longer period of time and thus reduce holdup. The present fuel velocity was very low to minimize the load put on the fuel pump.

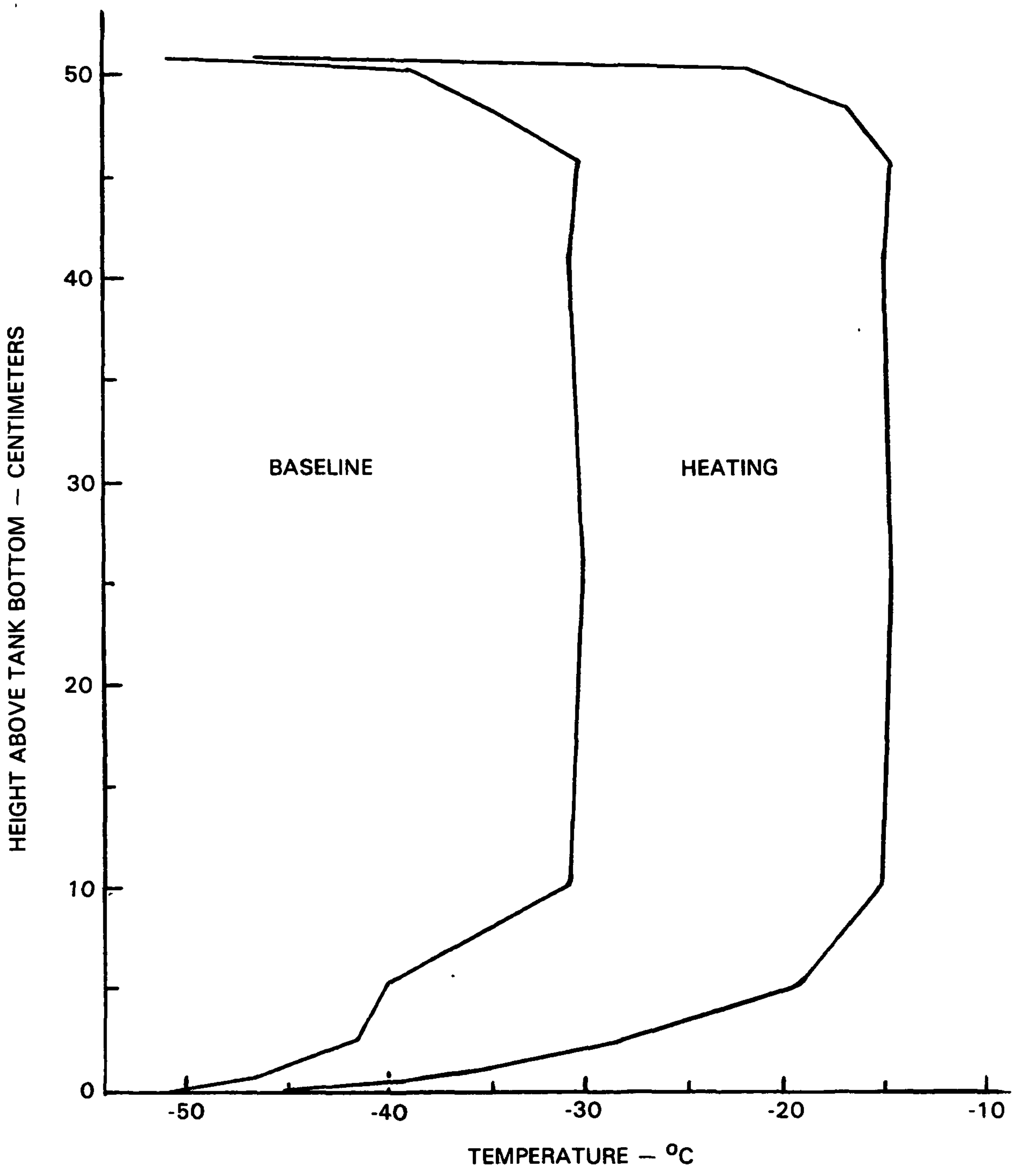


Figure 20 — Temperature Gradients, Baseline and 300 Watt Nominal Heating Continuous From Start, Tests 210 and 216, LFP-14 Fuel

TABLE 5

HORIZONTAL TEMPERATURE DISTRIBUTION PRIOR TO PUMPOUT, NO HEATING, TEST 210

HEIGHT CM	RACK 1 °C	RACK 2 °C	RACK 3 °C	RACK 4 °C	RACK 5 °C	SIDE 1 °C	SIDE 2 °C	SIDE 3 °C
50.8	-41.1	-50.7	-46.8	-47.9	-40.9			
50.2	-31.4	-38.6	-36.9					
48.3	-29.6	-34.8	-36.9	-30.4	-33.5			
45.7	-29.9	-30.3	-37.1					
40.6	-29.5	-30.7	-30.7	-30.7	-29.8			
25.4	-29.9	-30.1	-30.4	-30.3	-29.8	-30.9	-31.6	-30.8
10.2	-28.7	-30.7	-30.3	-31.3	-30.2			
5.1	-30.3	-40.2	-33.6					
2.5	-31.8	-41.6	-40.1	-40.8	-36.6			
1.3	-20.8	-45.3	-42.2					
0.6	-32.6	-46.9	-44.9					
0	-23.7	-50.5	-48.5	-44.3	-41.8			

TABLE 6

HORIZONTAL TEMPERATURE DISTRIBUTION PRIOR TO PUMPOUT FOR NOMINAL 300 WATT HEATING, TEST 216

HEIGHT CM	RACK 1 °C	RACK 2 °C	RACK 3 °C	RACK 4 °C	RACK 5 °C	SIDE 1 °C	SIDE 2 °C	SIDE 3 °C
50.8	-30.2	-46.5	-42.7	-33.4	-36.9			
50.2	-15.6	-21.7	-23.5					
48.3	-14.4	-16.8	-22.4	-14.9	-19.1			
45.7	-14.6	-14.6	-15.8					
40.6	-14.7	-15.0	-15.1	-15.1	-14.4			
25.4	-14.6	-14.6	-15.1	-15.1	-14.8	-17.4	-17.1	-17.1
10.2	-14.7	-15.1	-15.0	-15.2	-14.8			
5.1	-14.7	-19.3	-15.3					
2.5	-14.7	-27.7	-16.3	-33.1	-16.1			
1.3	-14.8	-34.4	-19.7					
0.6	-15.6	-38.4	-29.2					
0	-15.3	-46.2	-40.7	-38.5	-26.7			

7.3 CORRELATION OF HOLDUP

Figure 21 shows the relationship between percent mass holdup and the fuel temperature measured at 0.6 cm above the bottom of the tank. This type of analysis has been useful as a means of estimating holdup for setting new test conditions and for interpreting the solid-liquid state of the fuel during the test, prior to actual holdup determination by pumpout.

The boundary layer temperature 0.6 centimeters above the bottom surface was selected as a correlating parameter indicative of the boundary layer temperatures where solid fuel and wax accumulate. This correlation has been presented and discussed in Reference 12. It is evident that holdup is very sensitive to small temperature variations and considerable data scatter occurs. However, there is no systematic variation between the heated and unheated tests. Hence, heating the fuel reduces holdup by increasing the boundary layer temperature and not by any change in the mechanism of the phase change or solid agglomeration.

Another relationship to be considered is the solid-liquid interface temperature implying holdup level. This was shown in Figure 11, which indicated that this interface temperature is approximately the pour point. Hence, it is suggested that temperature profiles may be analyzed by estimating the solid, or potential holdup, volume as that occupied by fuel below the pour point. Further investigation of this analysis and its application to a range of fuel types was not attempted in the present study.

7.4 FUEL HEATING PROCEDURES

Heating rates were defined by the heat input to the recirculating fuel: 150,300, and (in one test) 600 watts. The objective of these tests was to represent the heated fuel temperatures and flow behavior, and not to optimize the system for maximum energy transfer. The stated heating rates are nominal values. In fact, it was obvious that the heat input to the fuel tank was considerably less than that used to power the electrical heater.

Heating was continuous from the test start for all but two tests. For these two tests, the oil was pre-heated from the test start, and when fuel heating was initiated (note Figure 13 for example), a temperature increase transient occurred from cooling of the preheated transport fluid. Subsequently, a more uniform heat transfer was obtained. This means of heating can be more effective in some cases, using energy to heat the fuel only when necessary. Whether or not fuel heating should be delayed in practical applications depends on the heating rate, oil reservoir capacity, test duration and temperature profile, fuel heating start time, and fuel used among other parameters.

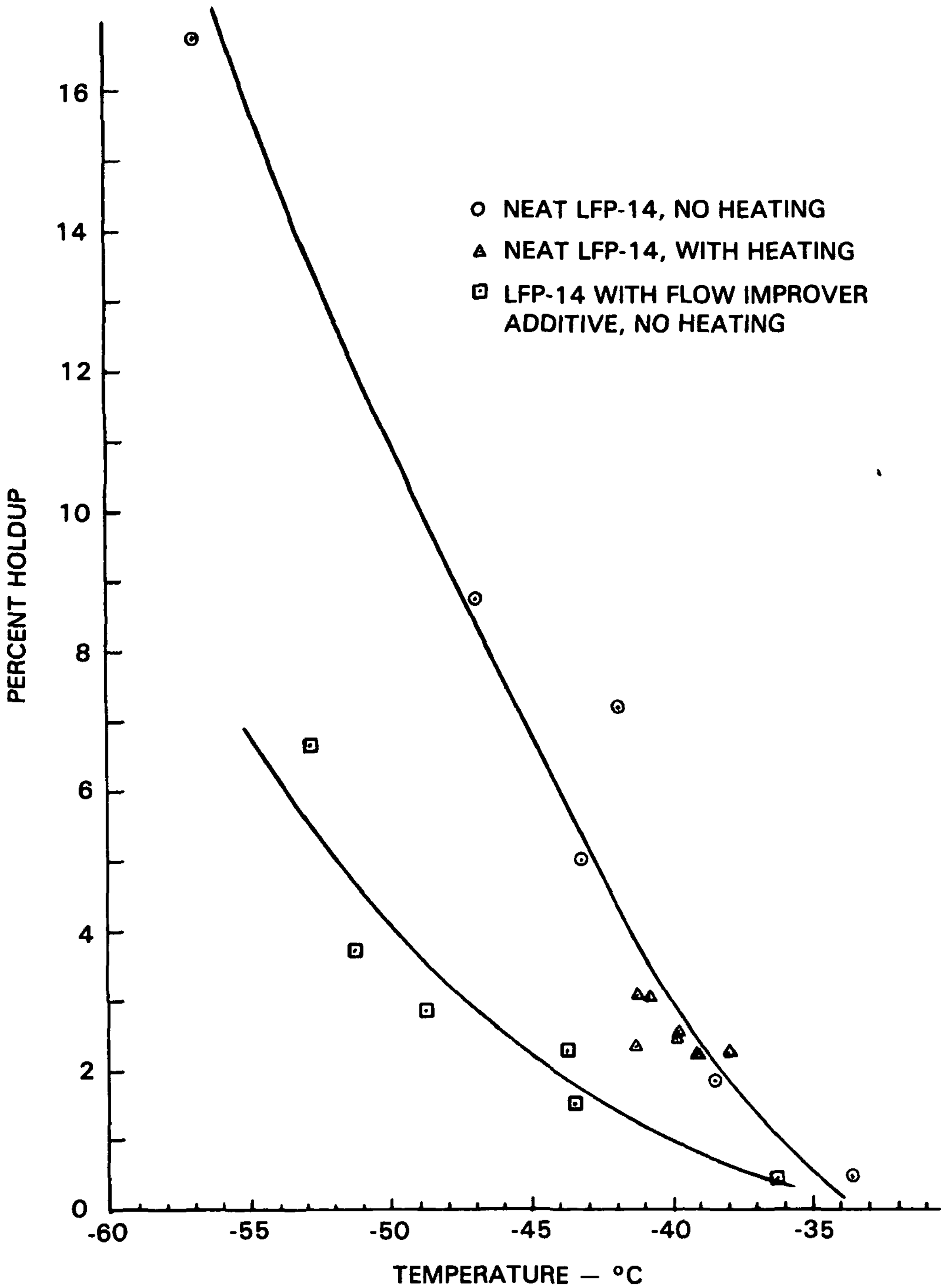


Figure 21 — Percent Holdup vs Temperature at 0.6 cm Above Bottom of Tank

8.0 CONCLUSIONS

Experimental tests were conducted with aviation turbine fuels subjected to low temperatures in a test tank. The test apparatus also contained a system for heating the fuel from heated MIL-L-23699 jet engine lubricating oil. The physical dimensions of the test tank represented a section of an outboard wing tank of a wide-bodied commercial airplane, and chilling was such that internal temperature profiles were comparable to those encountered in flight. Five fuels were tested: one was a production Jet A; three were higher freezing point experimental fuels; and one was a 70/30 mix of JP-5 and JP-8.

Flowability of the fuels was determined by withdrawing the fuel from the test tank and measuring the holdup, or unpumpable fuel remaining in the tank. Various combinations of temperature schedule, fuel recirculation distributor configuration, rate of heating, and heating procedure, as well as three flow improver additives, were evaluated for their effectiveness in reducing holdup.

The following conclusions resulted from this investigation:

1. Recirculation of heated fuel has a large effect on the bulk fuel temperature for all heating rates and procedures.

2. Recirculation of the heated fuel has a relatively small effect on fuel temperature in the boundary layer near the bottom surface of the tank. This is probably the result of convective flow in which the heated recirculating fuel moves upward in the tank. The colder descending fuel encounters the warm fuel, mixes, and the net result is little or no convective action in the bottom boundary layer.

3. Fuel heating has a measurable influence on reducing holdup. For situations which would produce holdups of 1% or 2% without fuel heating, the results of fuel heating are very small. For temperature conditions where greater holdup would occur, the influence of fuel heating becomes more pronounced. However, even high rates of heating may not reduce holdup below 1 to 2%, due to the presence of some subfreezing fuel near the chilled tank skin, following the baseline extreme cold day schedule.

4. Methods which increase penetration of heated fuel into the boundary layer at the bottom of the tank may improve fuel pumpability by reducing holdup. The "low re-entry cross flow" recirculation distributor, for instance, introduced the heated fuel approximately six centimeters lower in the tank than the single row distributor which was positioned above the bottom stringers, and reduced holdup in some cases.

5. Doping higher freezing point fuels with flow improver additives gives significant reductions in holdup. The effect is greatest for cases which would produce medium to large holdups without the additive. Cases which produced small holdups without additives showed only small improvements when doped.

6. Correlations of holdup based on boundary layer temperature can be applied in general to heated and non-heated test results. Each test fuel (and fuel/additive combination) has its specific correlation, which is useful in estimating holdup during a test.

9.0 RECOMMENDATIONS

Based on the scale model tank tests performed in this study, which investigated the effects of fuel heating in a low temperature environment, and the conclusions presented in the previous section, the following recommendations are made for future work.

1. Continue the systematic study of recirculation fuel heating. This should include analysis and control of heat transfer to fuel, variations in recirculation rates of fuel (particularly increased recirculation rates) and heat transport fluid, and experimental evaluation of recirculation distributor designs for improving penetration of heated fuel into the bottom boundary layer.

2. Continue the investigation of commercial flow improving additives to reduce holdup of aviation turbine fuels by a more systematic study of effective formulations, laboratory characterizations, and simulator tests to evaluate possible tradeoffs in which the use of additives could minimize heating requirements.

3. Tests should investigate whether the small amount of solid fuel holdup affects capacitance type fuel quantity gauging systems by altering the dielectric constant. It may be possible that a significant change in dielectric constant could lead to development of a holdup warning device.

APPENDIX A - CHRONOLOGICAL SUMMARY OF TESTS

Sh. 1 of 2

			Fuel							Heat Rate			Temperature Schedule					Recir. Dist			Heating					
Test No.	Date	Data Ref. No.	LFP-1	LFP-5	LFP-6	LFP-11 (JET A)	LFP-14	LFP-15	Additive	150 watts	300 watts	600 watts	Cold Fuel Holdup	Modif. Extr. Cold Day	Extreme Cold Day + W'd'l.	Standard Day	Total Test Time-Min.	Single Row Manifold	Low Re-entry Cross Flow	Low Re-entry Parallel Flow	Heat Early in Test	Heat at Spec. Temp.	% Holdup	Photos		Remarks
201	7/23/81	16285					X						X				120						.50	X		
202	7/24	16286					X						X				130						1.84			
203	7/28	16287					X						X				180						5.00	X		
204	8/13	16522					X						X				240						7.19	X		
205	8/14	16523					X						X				360						16.77	X		
206	8/18-8/19	16568					X						X				555						23.27	X		Test time includes 180 minute pre-cool.
207	8/20-8/21	17373					X						X				735						22.48	X		Test time includes 330 minute pre-cool.
208	8/31	16924					X							X			119						-			Cooldown rate inadequate.
209	9/3	16925					X							X			184						-			Cooldown rate inadequate.
210	9/21	16926					X							X			396						8.76	X		Baseline, extreme cold day.
211	9/25	16927					X			X				X			396		X			X	2.37	X		Heating after T.C. 18 = -26°C.
212	9/28	16928					X				X			X			396		X			X	2.53	X		Heating after T.C. 18 = -26°C.
213	10/1	17138					X									X	396						0			
214	10/5	17139					X								X		690						0			Some solids at lowest temp, subsequently melted.
215	10/12	17140					X			X				X			396		X		X		3.05	X		
216	10/13	17141					X				X			X			396		X		X		2.27	X		
217	10/14	17142					X					X		X			396		X		X		2.22	X		
218	10/19	17374					X			X				X			396			X	X		3.30	X		
219	10/20	17394					X				X			X			396			X	X		2.65	X		
220	10/22	17376					X			X				X			396	X			X		3.00			

APPENDIX A - CHRONOLOGICAL SUMMARY OF TESTS

			Fuel							Heat Rate			Temperature Schedule					Recir. Dist			heating					
Test No.	Date	Data Ref. No.	LFP-1	LFP-5	LFP-6	LFP-11(JET A)	LFP-14	LFP-15	Additive	150 watts	300 watts	600 watts	Cold Fuel Holdup	Modif. Extr. Cold Day	Extreme Cold Day + W'd'l	Standard Day	Total Test Time-Min.	Single Row Manifold	Low Re-entry Cross Flow	Low Re-entry Parallel Flow	Heat Early in Test	Heat at Spec. Temp.	% Holdup	Photos		Remarks
221	10/23/81	17377					X				X			X			396	X			X		2.43	X		
222	10/26	17378		X						X				X			396	X			X		8.50	X		
223	10/27	17379		X							X			X			396	X			X		10.39	X		
224	10/28	17380		X									X				141						22.07	X		No slow through pump. Partially drained through recirculation tube
225	11/16	17395				X											400						- -			Duplicate of aircraft history (10/21/81, -21.4° C Min.).
226	12/10	17631					X		X				X				360						6.65	X		Temperature schedule of Test No. 205.
227	12/14	17632					X		X				X				300						3.73	X		Temperature Schedule of Test No. 205 but 300 minutes.
228	12/15	17633					X		X				X				255						2.83	X		Temperature Schedule of Test No. 205 but 255 minutes.
229	12/16	17634					X		X					X			396						2.28	X		Compare with test 210 for effect of additive.
230	12/17	17635					X		X				X				180						1.53	X		Temperature Schedule of Test No. 205 but 180 minutes
231	12/18	17636			X								X				139						6.63	X		Duplicate of Test No. 42 (8/25/78, 6.6% holdup)
232	12/22	17637			X				X				X				139						4.29			Temperature Schedul. of Test No. 42.
233	12/23	17638			X				X				X				97						3.38	X		Temperature Schedule of Test No. 42 but 97 minutes.
234	1/5/82	18282		X									X				146						6.71	X		Duplicate of Test No. 86 (11/3/78, 6.8% holdup)
235	1/7	17966		X					X				X				146						4.64	X		Temperature Schedule of Test No. 86.
236	1/8	17967		X					X				X				65						1.64	X		Temperature Schedule of Test c. 86 but 65 minutes.
237	1/29	17968					X		X				X				100						0.46	X		Temperature Schedule of Test No. 205 but 100 minutes.
238	2/2	18283						X					X				315						4.94	X		Temperature Schedule of Test No.92 (12/13/78, 5.2% holdup, Jet A).
239	2/4	18284						X	X				X				315						4.93	X		Same as above.
240	2/8	18281	X						X				X				351						5.93	X		Temperature Schedule of Test No. 60 (9/28/78, 6.5% holdup, LFP-1.

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15 Supplementary Notes

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16 Abstract

These tests are a continuation and extension of previously reported tests performed on an aircraft outer wing tank simulator chilled in the upper and lower surfaces Fuel could be pumped from the simulator, heated by lubricating oil in an external heat exchanger, and returned to the simulator tank The principal fuel was an experimental aviation turbine fuel with a freezing point somewhat higher than present specifications Tests conducted at temperature schedules representing extreme cold weather conditions provided the baseline data for comparisons. Fuel heating superimposed on the baseline conditions increased the bulk fuel temperature appreciably, and the boundary layer temperatures near the chilled surfaces to a lesser extent Consequently, fuel heating improved flowability as measured by the reduction in holdup, defined as the unpumpable fuel remaining in the tank after withdrawal of the liquid fuel Increased heating rates, however, provided only small further improvements in flowability Doping the fuel with a proprietary flow-improving additive also resulted in significant reductions in holdup Use of the additive showed promise as an alternative to fuel heating

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